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WASTE MANAGEMENT IMPLICATIONS OF CONCENTRATING SLIMES - CHARACTERISTICS AND POTENTIAL PROBLEMS

by

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ABSTRACT

This report describes the geotechnical, geochemical and environmental characteristics of fine-grained uranium tailings (slimes) which may influence both short- and long-term management of slime-enriched uranium tailings impoundments. Properties of slimes are compared and contrasted with those of sand tailings using field and laboratory data primarily from naturally segregated tailings in the Elliot Lake area, Ontario and Northern Saskatchewan uranium-bearing regions of Canada.

Slimes may be generally characterized as silt-sized particles (less than 200 mesh or 75 microns) with high water contents, relatively low permeability, low density and high compressibility relative to sand tailings. Plasticity indices range from low to high depending on clay content and mineralogy of the parent ore; Elliot Lake slimes are almost non-plastic, while Northern Saskatchewan slimes exhibit high plasticity.

Radionuclides such as Ra-226 and Pb-210 are strongly associated with the fine particle fraction, and data from northern Saskatchewan slimes suggest that trace metals follow a similar pattern. In pyritic tailings (Elliot Lake) most of the metals are associated with pyrite and thus distributions are similar in coarse and fine tailings. Pyritic tailings generally exhibit low pH's and high concentrations of soluble metals, sulphate and radionuclides. However, due to the high water retention capacity of slimes, pyrite oxidation is inhibited and soluble contaminant concentrations may be lower than in coarse-grained tailings. Similarly radon gas exhalation from slimes may also be lower due to lower diffusion coefficients through the saturated tailings.

Reclamation of slimes by revegetation has been unsuccessful to date. Poor aeration of the root zone appears to be the major growth limiting factor, although under aerobic conditions, low pH and high concentrations of toxic element would inhibit growth.

Key management considerations for slime-enriched tailings areas include:

- overall mass stability
- drainage/settlement and site accessibility
- dusting/water erosion

- o overall water balance/seepage
- o reclamation

Management alternatives are discussed in terms of interactions between geotechnical, geochemical and biological processes.

RÉSUMÉ

Ce rapport présente les caractéristiques géotechniques, géochimiques et environnementales des résidus de mines d'uranium composés de fines particules (boues) qui peuvent influer sur la gestion à court et à long termes des réservoirs de stockage de ce genre de résidus d'uranium. Afin de déterminer ces caractéristiques, les propriétés des boues sont comparées et confrontées avec celles des résidus de mines sablonneux sur la base des données de terrain et de laboratoire qui proviennent principalement de résidus séparés naturellement de deux régions uranifères du Canada, soit celle d'Elliot Lake (Ontario) et celle des régions du nord de la Saskatchewan.

Les boues sont composées de particules de la grosseur du limon (moins de 200 mailles ou de 75 microns). Ces boues ont en général une teneur élevée en eau, une perméabilité et une densité relativement faibles et une forte compressibilité en comparaison des résidus sablonneux. Les valeurs des indices de plasticité varient entre faibles et élevées suivant la teneur en argile et les caractéristiques minéralogiques du gisement originel; le degré de plasticité des boues d'Elliot Lake est faible alors que celui des boues des régions du nord de la Saskatchewan est relativement élevé.

Les éléments radioactifs tels le radium 226 et le plomb 210 sont souvent associés avec la fraction de particules fines. Les métaux à l'état de trace semblent suivre ce même modèle selon nos données sur les boues du nord de la Saskatchewan. Cependant, pour les résidus pyriteux (Elliot Lake), la plupart des métaux sont associés avec la pyrite et ainsi les répartitions entre les résidus composés de particules fines et grossières sont semblables. Les résidus pyriteux ont généralement un faible pH et de fortes concentrations de métaux, de sulfates et de radionucléides solubles. Cependant, en raison de la grande capacité de rétention d'eau des boues, l'oxydation de la pyrite est limitée et les concentrations des contaminants solubles peuvent être moindre dans les résidus composés de particules fines que dans les résidus de particules grossières. Pareillement, l'exhalation du gaz radon des boues peut aussi être moindre en raison de plus faibles coefficients de diffusion à travers les résidus saturés.

La récupération des boues par la revégétation est jusqu'à maintenant un échec. La raison principale de cette croissance limitée semble être la mauvaise aération à la hauteur des racines, malgré que dans des conditions aérobies, le faible pH et les fortes concentrations des éléments toxiques empêcheraient la croissance.

Les points à considérer pour la gestion des résidus enrichis de boues sont :

- stabilité de la masse totale,
- drainage/tassement et accessibilité du site,
- poussière/érosion par l'eau,
- équilibre d'eau/infiltration, et
- récupération.

Les options de gestion sont examinées par rapport aux interactions entre les processus géotechniques, géochimiques et biologiques.

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1.0 INTRODUCTION

1.1 Overview

Structural backfilling has been practiced in the past and is proposed as a future activity at some uranium mines in Canada. In this process, the mill tailings are mechanically separated into coarse and fine-size fractions. The coarse fraction is then used to raise the working floor (as, for example, at Beaverlodge) or for secondary pillar recovery (at Denison Mines). The fine fraction, known as slimes, is disposed of in a containment area. This practice has a number of economic advantages over standard surface disposal methods in that it represents more efficient resource use and may significantly reduce the volume of tailings to be disposed of. There are, however, a number of associated problems related primarily to the disposal and management of the slime fraction.

Slimes are composed of silt-sized particles, rock flour and secondary mineral precipitates (sulphates, aluminates silicates and hydroxides). Although no precise definition of slimes exists, in the uranium industry in Canada, they are generally considered to be that fraction of the tailings which are predominantly less than 200 mesh or 75 microns in size.

The proportion of slimes produced within any given milling operation will depend upon the nature of the ore and the fineness of grind needed to ensure efficient recovery. The chemical and physical characteristics of the secondary mineral precipitates found in the slime fraction is also dependent upon the nature of the ores being milled, the chemical leaching conditions under which the uranium was extracted and the particular treatment process used to treat the tailings prior to their segregation or discharge.

The physical and chemical properties of concentrated slimes are highly interdependent and differ from those of unsegregated tailings in many respects. The presence of newly formed secondary minerals and a large fresh mineral surface area result in slimes having greater water retention capacity and higher adsorption coefficients for trace elements and radionuclides than the more coarse tailings fraction. These factors, in turn, influence geotechnical and environmental parameters, such as structural stability, drainage, and potential toxicity to microorganisms, vegetation and downstream aquatic organisms. In order to assess the overall attractiveness of slimes segregation and/or milling technologies which produce tailings with a high slimes content, it is necessary to

evaluate the implications of managing slime-enriched tailings areas, over both the short- and long-term.

This study addresses the following specific areas as they relate to geotechnical, geochemical and environmental aspects of the management of slime-enriched tailings:

- the methods of sand-slimes separation both through natural segregation during placement and artificial segregation prior to placement;
- the geotechnical properties of slimes that influence their physical stability and biological characteristics;
- the geochemical properties of slimes that affect chemical stability and biological characteristics; and
- those interactions between the geotechnical, geochemical and biological variables which influence management decisions in slime-enriched tailings areas.

Based upon an evaluation of the above areas, conclusions are drawn as to the relative overall acceptability of slime-enriched tailings as they may affect the local environment in both the short- and long-term.

The final section of the report addresses data gaps that have been identified in carrying out this work, and makes recommendations as to specific research needs.

This report was prepared by Beak Consultants, in association with Golder Associates, and with contributions to mining aspects of uranium tailings by F.C. Lendrum Consulting Ltd.

2.0 CHARACTERISTICS OF SLIME-ENRICHED TAILINGS

2.1 Introduction

The composition and properties of uranium mill tailings depend on the original ore type and the milling process used. In Canada, the sulphuric acid leach process has been used almost exclusively (with the exception of the Beaverlodge operation) on all ore types. This process requires only a relatively coarse grind, and generally the mill-feed consists of 50% less than 200 mesh (75 micron diameter) particles.

In the past, the leach residues and spent leach solution were generally discharged directly to tailings impoundments after neutralization to pH values of about seven. Later, lime addition raised pH values to between 8 and 11 prior to discharge. Lime treatment also resulted in the formation of many precipitates such as ferric hydroxides and gypsum that were combined and discharged with the solids.

Separation of fine- and coarse-grained fractions of the tailings prior to discharge results in a significant increase in the percentage of less than 200 mesh particles that are deposited in the impoundment. The relative concentration of secondary precipitates also increases in the slime-enriched fraction. The relative quantity of these precipitates vary with the ore type, but generally comprise 5 to 10% of the total solids in unsegregated tailings with greater concentrations in the fines. The presence of these secondary solids influence both geochemical and geotechnical properties of the tailings.

2.2 Ore Types

Three basic types of ore have been exploited for uranium in Canada:

- o uraninite mineralization occurring in pegmatites;
- o pitchblende mineralization in quartz-pebble conglomerates (reef-type); and
- o pitchblende and brannerite mineralization as veins often associated with an unconformity below the Athabaska formation.

Pegmatite Ores

The pegmatitic ores are characterized by significant concentrations of U, Th, rare earth elements (REE), Mo, Nb and Ti. Accessory minerals are generally composed of non-reactive low temperature varieties. This ore type is found in Bancroft, Ontario where mining was conducted at the Bicroft, Faraday and Madawaska properties between about 1957 and 1963. The mining region is now inactive and about 4×10^6 tonnes of tailings covering approximately 25 hectares remain in the area (Melis, 1983). For economic reasons, further exploitation of uranium in this region is not expected. No sand-slime segregation for mining backfill purposes, was practiced in this area and slimes occur only in local pockets in tailings where natural segregation has occurred.

Reef-Type Ores

The conglomeratic ores are characterized by the presence of U, Th, Ti, REE, Au and Zr. Although quartz is the most abundant accessory mineral, pyrite is important because of its reactivity. This ore type is found in the Elliot Lake region of Ontario. Eight mining properties have been developed in the region. Four mines are currently in operation (Quirke, Panel, Stanleigh and Denison). The total quantity of existing tailings is estimated to be about 100×10^6 tonnes covering an area of about 450 hectares. Under present conditions, mining is expected to continue until about 2020. Some limited sand-slime segregation has been carried out in this area to obtain sands for pillar recovery and more is expected in the future.

Vein-Type Ores

The vein-type ores vary in character from simple uranium mineralization to complex assemblages containing high concentrations of metals and other elements (notably, Ni and As). The classical vein deposits occur in igneous and metasedimentary rocks along major fault zones. The unconformity related deposits, which are generally more complex mineralogically, occur in and around the metasedimentary units of the Athabaska formation. This variety of vein deposits is usually very high grade with some zones containing 10% or greater U_3O_8. Vein-type ores are found in various locations in northern Saskatchewan and Northwest Territories. There are a total of eight mining properties, three of which are presently active. The high ore grades, found in the

unconformity-type deposits, currently suggest that they will become the dominant source of uranium in Canada. Further mining and milling can, therefore, be expected in this region. Most high-grade ores are currently mined by open-pit method and, therefore, backfilling of sand-enriched fractions of tailings would be considered only when underground operations commence.

2.3 Applicability of Current Tailings Placement Methods to Slime-Enriched Tailings

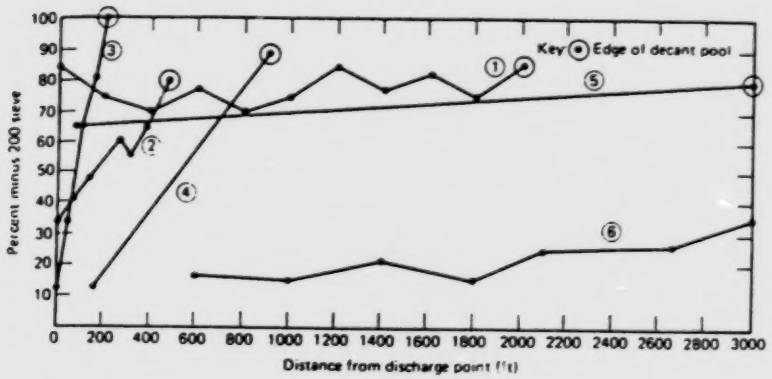
2.3.1 Pipe Discharge

Historically, uranium tailings have been discharged through pipe lines in slurry form, containing approximately 25% (by weight) solids, to impoundments generally occupying topographic lows. Tailings dams have, in the past, been constructed to confine solids to the impoundment area with little concern for long-term stability or seepage control (Moffett, 1976). More recently, however, consideration has been given to dam stability in terms of future decommissioning. Seepage has been reduced by incorporation of low permeability cores within the dam structures.

Whether single-point or multiple-point (spigots) discharge is used, tailings deposits develop certain characteristics in terms of grain size distribution. Segregation occurs in the tailings impoundment resulting in differing grain size distributions with distance from the discharge pipe. Examples of such segregation are given in Figure 2.1 for a variety of semi-precious and base-metal mine tailings. Tailings numbers 2 and 4 in this figure have distributional characteristics similar to uranium tailings in Canada, even though slurry (pulp) densities are somewhat higher. For lower slurry densities (approximately 25%) that are typical for uranium tailings, it is expected that greater segregation with distance will occur. This will result in greater concentrations of the fine-grained fractions at distal regions from the discharge area.

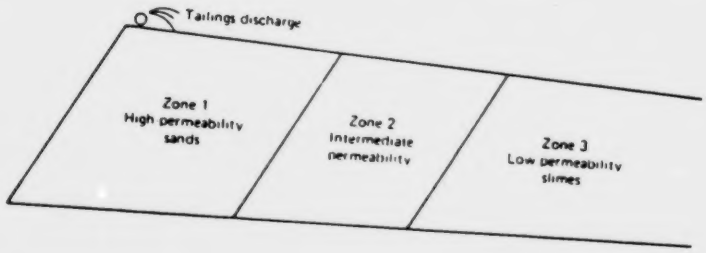
As a result of grain-size segregation, the hydraulic conductivity of the tailings will also vary with location within the impoundment. Larger fractions of fine-grained material results in lower hydraulic conductivities. The relative spatial distribution of hydraulic conductivity within tailings is shown schematically in Figure 2.2. This distribution directly reflects that of grain-size.

FIGURE 2.1: GRAIN-SIZE SEGREGATION ON TAILINGS BEACHES SHOWING TAILINGS TYPE, SPECIFIC GRAVITY (G), PERCENT MINUS 200 MESH AND SLURRY (PULP) DENSITY (Vick, 1983)



Curve	Tailings type	G	%−200, Mill discharge	Pulp density of mill discharge	Source
1	gold	–	–	–	Blight and Steffen, 1979
2	copper	2.7	45	45	Volpe, 1979
3	lead-zinc slimes	3.4	75	< 40	Unpublished
4	–	2.7	38	30	Soderberg and Busch, 1977
5	–	2.7	60	50	Soderberg and Busch, 1977
6	copper	3.0	–	–	Unpublished

FIGURE 2.2: CONCEPTUAL REPRESENTATION OF PERMEABILITY (HYDRAULIC CONDUCTIVITY) VARIATION WITHIN A TAILINGS DEPOSIT (VICK, 1983)



2.3.2 Thickened Tailings Disposal

The thickened tailings disposal system stems from a concept first described by Shields (1974) and further developed by Robinsky (1979). It consists of discharging tailings with a relatively thick consistency (on the order of 60% solids) such that the tailings form a cone. The tailings are discharged in a conical pile that typically develops a slope of 2 to 4% with very little segregation in grain size. Higher values in the density of the tailings slurry results in less segregation as shown in Figures 2.3a and 2.3b.

An experimental trial cone of thickened tailings was constructed with unclassified Denison tailings (Chakravatti et al., 1982). When the solids content was increased to about 70%, uniform deposition was found to occur across the cone at a slope of about 3.4%.

Robinsky (1982) concluded that earthquake effects are considered to be minimized for tailings discharged by the thickened tailings disposal method and deposited at a 4 to 6% slope. In contrast, Jeyapalan (1982) concluded that tailings are susceptible to liquefaction and flow sliding under moderate seismic events, with 6 to 8 degree slopes deforming to a slope of 0.5 to 2 degrees. The liquefaction resistance of tailings thus deposited is, therefore, unresolved at this time.

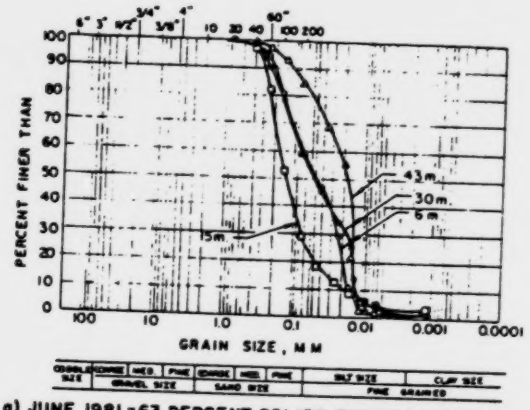
It should also be noted that Vick (1983) observed that thickened tailings disposal is only applicable for tailings containing a reasonable sand fraction and without a major proportion of clayey fines. In view of this, the use of slime-enhanced tailings may lead to greater difficulty in employing the thickened tailings discharge method.

2.3.3 Sub-aerial Tailings Deposition

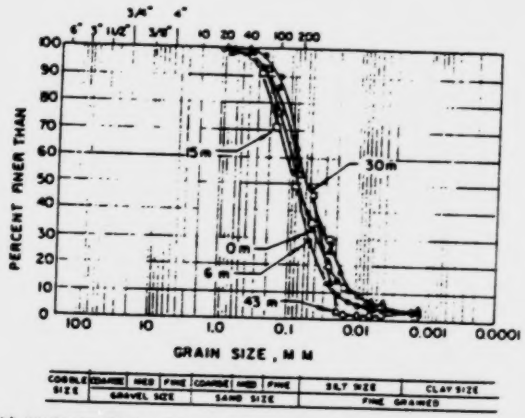
The sub-aerial tailings deposition method is described by Knight and Haile (1983). It is being used at the Key Lake uranium project in Saskatchewan.

Knight and Haile detailed the method, which is designed to involve the systematic deposition of tailings in thin layers, with each layer allowed to settle, drain and partially air dry prior to covering with a further layer. From their paper, the tailings slopes (between 1 and 2%) do not differ from those in conventional hydraulically deposited tailings areas.

FIGURE 2.3: GRADATION ANALYSIS AT VARYING DISTANCES FROM THE CENTRE OF THE CONE OR DISCHARGE OUTLET. (CHAKRAVATTI et al., 1982)



a) JUNE 1981 - 63 PERCENT SOLIDS TAILINGS SEGREGATING



b) AUGUST 1981 - 70 PERCENT SOLIDS UNIFORM TAILINGS

The tailings at Key Lake are a sandy silt of low plasticity (35% fine sand, 65% silt and amorphous precipitates). Because the tailings include a high percentage of gypsum, the settled density under water at a typical solids content of 30% by weight was only 4 kN/m^3; when allowed to drain, this increased to 4.8 kN/m^3. When air dried to 80% water saturation, the density increased to 8.4 kN/m^3. It is not known whether such evaporation has been realized in the field, leading to this significant increase in density.

Laboratory testing of the tailings from Key Lake by Knight and Haile (1983) indicated an angle of internal friction of 45 degrees, a vertical coefficient of hydraulic conductivity of 7×10^{-8} cm/sec and a coefficient of consolidation, c_v, of 4.4 to 36.6 m^2/yr.

The possible effect of slime enhancement on the viability of the sub-aerial tailings technique is not clear. Theoretically, there would seem to be no reason for it not to work, but practically it would appear that the time for drainage and air-drying would be increase with an increase in slime content. Given the general climatic conditions in Canada, a high slime content may render the method inoperable.

Typical slurry discharge of slime-enriched tailings, of which 25% is solid material, would likely result in significant segregation of the slime-enriched fraction across the tailings impoundment. In this case, the grain-size distribution would consist of fine-sand or coarse silt on the beach to fine-silt and clay-size particles at the distal section of the impoundment. Such segregation is shown in Case 3 in Figure 2.1 in which 75% of the tailings originally consisted of minus 200 mesh particles. As a consequence of severe segregation, all particles from about 60 m beyond the discharge pipe were minus 200 mesh in size.

2.4 Geotechnical Properties of Uranium Tailings Slimes

The engineering properties (permeability, consolidation and shear strength) and overall behaviour (liquefaction potential and slope of deposition) of uranium tailings slimes are dependent on a combination of many factors. These include index properties by which tailings are characterized (e.g., gradation, specific gravity and plasticity), as well as parameters which describe the tailings during deposition and after they have settled (e.g., the water content and density). This section of the report summarizes available information on Canadian uranium tailings slimes and, in particular, assesses the

geotechnical implications of existing or proposed uranium mining developments which contain or will generate areas of slime-enriched tailings. In Table 2.1, geotechnical characteristics of slimes from Elliot Lake and northern Saskatchewan tailings are compared with those of sand tailings.

2.4.1 Index Properties

Index properties by which tailings are characterized include gradation, plasticity and specific gravity.

Sources of information relating to the index properties of uranium slimes from both the Elliot Lake area of Ontario and northern Saskatchewan include:

- laboratory and field testing carried out on tailings slimes obtained from the Denison Mines Tailings Management Area in Elliot Lake (Golder Associates, 1980, 1982a, 1984; Conlin, 1980; Matyas et al., 1984);
- the results of testing carried out on tailings slimes from Rio Algom's Quirke Mine Tailings Management Area in Elliot Lake (Golder Associates, 1977, 1979; Matyas et al., 1984);
- the results of testing carried out on a tailings test bed which was considered characteristic of tailings to be produced at the Midwest Lake Uranium Mine (Golder Associates, 1984);
- the results of testing carried out on tailings from Cluff Lake, Saskatchewan (Golder Associates, 1983a); and
- laboratory testing carried out on tailings obtained from Mine Water Lake, Meadow Lake and Ace Creek Discharge Area at Eldorado's Beaverlodge operation in Saskatchewan, which has since been closed (Golder Associates, 1982b).

Grain Size Distribution

The grain size characteristics of mine tailings will depend on the mineralogy of the ore-bearing rocks and the process used to extract the uranium. In general, uranium tailings are relatively coarse, containing either principally sands or non-plastic, silt-sized particles exhibiting sand-like behaviour.

TABLE 2.1: SUMMARY OF TAILINGS CHARACTERISTICS

Tailings Characteristics	ELLIOT LAKE		NORTHERN SASKATCHEWAN	
	Slimes	Sands	Slimes	Sands
A. GEOTECHNICAL AND ENGINEERING PROPERTIES				
I. Index Properties				
o Grain Size	silt with some sand (1-400 um)	fine-medium sand, silty sand (60-10,000 um)	silt with some sand (800-2,000 um)	fine-medium sand, silty sand (800 to 2,000 um) *Beaverlodge (to less than 75 um)
o Plasticity	Non-plastic	non-plastic	non-plastic to plastic	non-plastic
- Liquid Limit (%)	33 (average)	-	0 to 101	-
- Plastic Limit (%)	31 (average)	-	0 to 81	-
- Plasticity Index (%)	2 (average)	-	0 to 20	-
o Specific Gravity (g/cm^3)	2.67 (average)	2.73 (average)	2.55 to 3.08	-
II. In Situ Properties				
o Water Content (%)				
- Surface	100 to 105	35	66 (Beaverlodge)	(values lower than expected)
- Deep (12 m)	30 to 50	30	9	
o In Situ Density (KN/m^3)				
Total Unit Weight				
- Surface	13.3	16.5*	-	-
- Deep (15 m)	16.5	19.6*	-	-
Dry Density				
- Surface	6.3	11.8*	4.0 to 9.0**	-
- Deep (15 m)	10.2	15.7*	-	-
Relative Density (%)				
- Above Water Table	-	30 to 100	-	-
- Below Water Table	0 to 50	0 to 70	-	-
III. Engineering Properties				
o Permeability (cm/s)	10^{-5} to 10^{-6}	10^{-3} to 10^{-4}	10^{-5} to $4x10^{-8}$	10^{-5} to $4x10^{-7}$
- Laboratory	10^{-5} to 10^{-8}	10^{-3} to 10^{-4}	10^{-5} to $4x10^{-8}$	10^{-5} to $4x10^{-7}$
- Field	$3x10^{-3}$ to $3x10^{-4}$	10^{-2} to $3x10^{-5}$	-	-
o Compression Index	0.2 to 0.45	0.04 to 0.1	-	-
o Coefficient of Consolidation (cm^2/s)	$5x10^{-4}$ to $2x10^{-3}$	$5x10^{-2}$ to $2x10^{-1}$	-	-
o Drained Shear Strength	36^o to 46^o	30^o to 41^o	45^o**	-
o Undrained Shear Strength (kPa)				
- Surface	-	-	-	-
- Deep (3 m)	9.8 to 14.4	-	-	-
o Cyclic Shear Strength				
- Stress ratio at 6 cycles	0.3 (average)	0.3 (average)	-	-

* Limited data.
** Data for Key Lake tailings.

TABLE 2.1: SUMMARY OF TAILINGS CHARACTERISTICS

Tailings Characteristics	ELLIOT LAKE		NORTHERN SASKATCHEWAN	
	Slimes	Sands	Slimes	Sands
B. GEOCHEMICAL PROPERTIES				
I. Tailings Solids				
o Ore Type	Reef Ores		Unconformity and Vein Type Ores	
o Minerals (relative concentrations)				
- Gypsum (%)	10-12	1-4	(30) est.	(5)
- Carbonate (%) (Calcite)	0.2	0.005	(5)	(5)
- Iron (%) ($Fe(OH)_3$)	3	0.5	-	-
- Pyrite (FeS_2)	3-7	3-7	little or no pyrite	
o Radionuclides				
- Ra-226 (pCi/g)	100-500	100-200	(9,000)*	(1,500)*
- Pb-210 (pCi/g)	100	100		
- Po-210 (pCi/g)	50	50		
- U (ug/g)	10-100	10-100		
- Th (ug/g)	10-300	10-300		
o Other Constituents				
- Fe	-	-	(4.3%)**	(1.8%)
- Cu	-	-	(0.06%)	(0.02%)
- Zn	-	-	(0.08%)	(0.01%)
- Ni	-	-	(2.5%)	(0.6%)
- Co	-	-	(0.09%)	(0.06%)
- Pb	-	-	-	-
- As			(2.3%)	(0.3%)
II. Pore Water Chemistry				
o Radionuclides				
- Ra-226 (pCi/L)	10-300	10-300	-	-
- Pb-210 (pCi/L)	5-50	50-5,000	-	-
- Po-210 (pCi/L)	-	-	-	-
- U (ug/L)	50-200	100-5,000	-	-
- Th (ug/L)				
o pH				
- discharge	9-11	9-11	-	-
- weathered	3-6	1-5	-	-
o Other Constituents (mg/L)				
- Al	1-30	1-200	-	-
- SiO_2	20-120	20-120	-	-
- Ca	400-600	400-600	-	-
- Mg	10-250	10-400	-	-
- Na	10-40	10-40	-	-
- K	10-130	10-170	-	-
- SO_4	1,500-10,000	10,000-150,000	-	-
- PO_4	0-2	0-2	-	-

TABLE 2.1: SUMMARY OF TAILINGS CHARACTERISTICS

Tailings Characteristics	ELLIOT LAKE		NORTHERN SASKATCHEWAN	
	Slimes	Sands	Slimes	Sands
- Fe	50-5,000	1,000-30,000	-	-
- Cu	0-5	0-10	-	-
- Zn	5-20	1-50	-	-
- Ni	1-5	1-30	-	-
- Co	0-4	1-30	-	-
- Pb	0-0.5	0-4	-	-
- Mn	20-200	0-30	-	-

* Estimated concentrations based on 90% of Ra-226 remaining in slimes with slimes comprising 60% of the total original solids.

** Estimated concentration based on the amount of each constituent in the ore and the percent of each that is solubilized in the mill. All of the dissolved fraction is assumed to enter the slimes during neutralization.

- Indicate data unavailable.

The gradation of typical mill tailings prior to discharge and the gradation ranges for coarse (sand) and fine (silt) tailings from Elliot Lake are shown on Figure 2.4. This is based on more than 100 determinations carried out between 1971 and 1981 and reflects the difference in gradation which occurs generally after discharge into a tailings basin; the coarser tailings (predominantly a fine to medium sand to a silty sand) are deposited nearer the pipeline discharge, while the finer fraction (silt-sized fraction with some sand) are carried down closer to the decant.

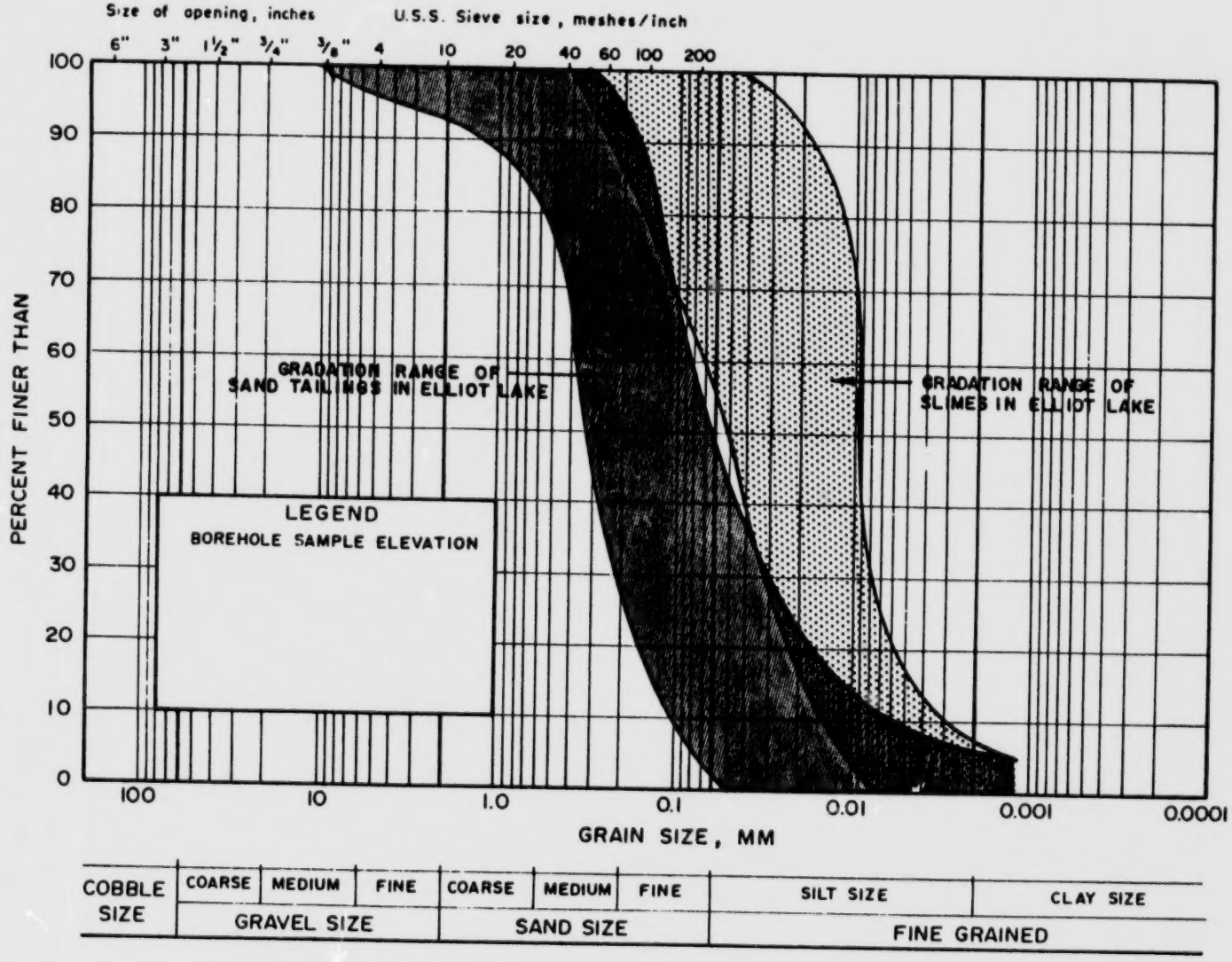
The gradational characteristics of uranium slimes from Saskatchewan are shown in Figure 2.5. Gradation ranges for Saskatchewan uranium slimes are generally similar to those of slimes in Elliot Lake, with the exception of the finer slimes from Eldorado's Beaverlodge operation. This was an alkaline-leach process which required grinding of the ore to a finer size (predominantly minus 200 mesh) compared to the coarser acid-leach tailings. These finer alkaline-leach slimes are similar in gradation to fine tailings such as some phosphate or bauxite tailings, but because all the active and proposed uranium mines in Canada use an acid-leach process, the finer alkaline-leach tailings are not considered further in this report.

Tailings were segregated for backfill purposes at Beaverlodge in Saskatchewan. Grain size analyses indicate that the slime fraction is almost all finer than 325 mesh (44 micron diameter), while the coarse fraction consists of more than 60% greater than 325 mesh or 36% greater than 200 mesh (Table 2.2). Because Beaverlodge tailings were originally finer than other tailings arising from the acid leach process, segregation of other such tailings would not be expected to result in such a fine slime fraction.

Plasticity

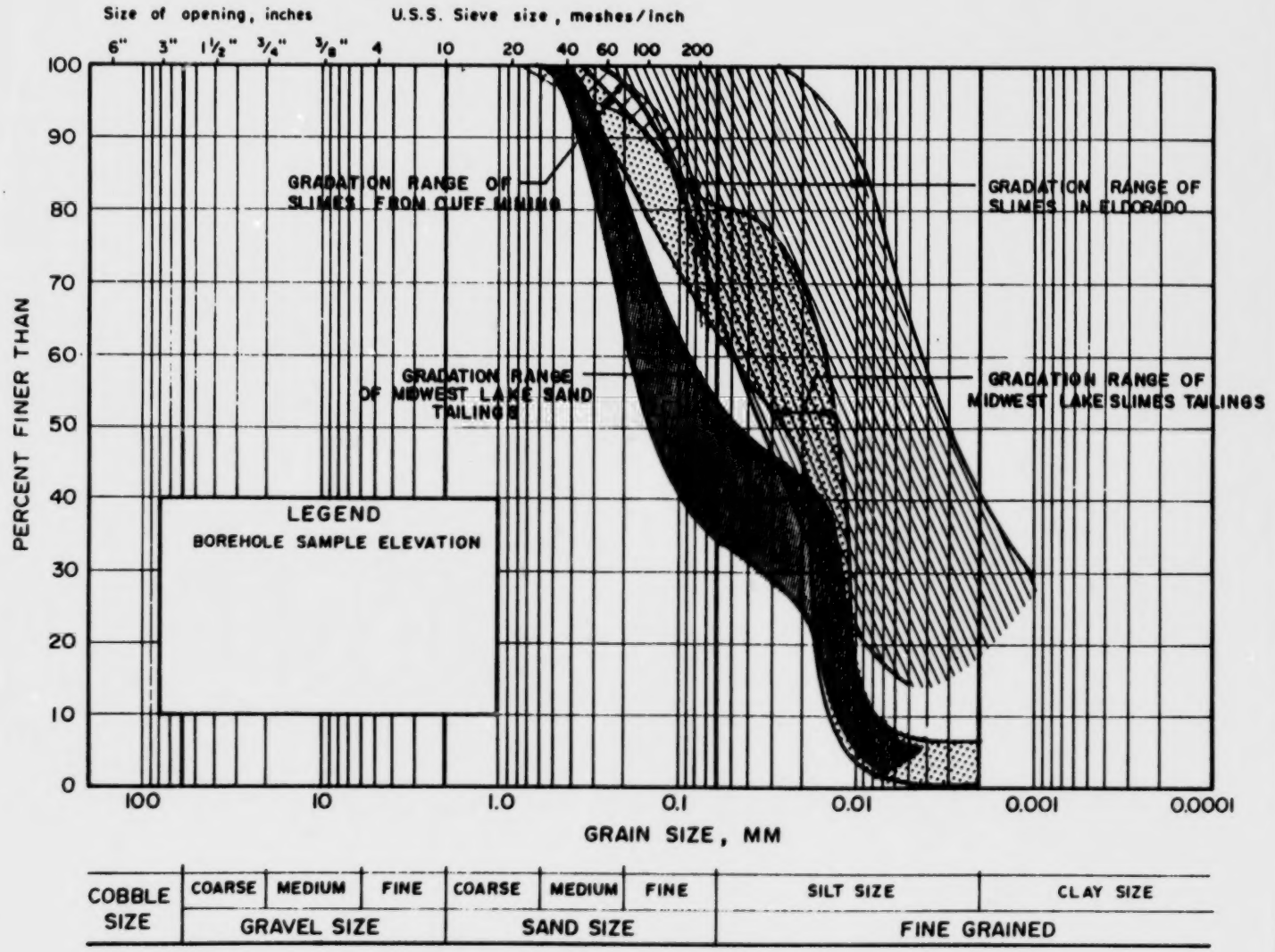
Because of their relatively high sand content, whole uranium tailings (sands and slimes together) are usually non-plastic (Vick, 1984). However, the plasticity of the slimes fraction (which is measured by the Atterberg limits and plasticity index) can vary from low to high, depending on the clay content and mineralogy of the parent ore.

Atterberg limits of slimes from Denison Mines Tailings Management Area in Elliot Lake were measured in nine tests. The average liquid limit was 33%, the average plastic limit was 31% and the average plasticity index was 2%. These slimes are, therefore, almost non-plastic.


Size of opening, inches
U.S.S. Sieve size, meshes/inch
6" 3" 1½" ¾" ⅜" 4 10 20 40 60 100 200
PERCENT FINER THAN
100 90 80 70 60 50 40 30 20 10 0
GRADATION RANGE OF SAND TAILINGS IN ELLIOT LAKE
GRADATION RANGE OF SLIMES IN ELLIOT LAKE
LEGEND
BOREHOLE SAMPLE ELEVATION
100 10 1.0 0.1 0.01 0.001 0.0001
GRAIN SIZE, MM
COBBLE SIZE
COARSE MEDIUM FINE
GRAVEL SIZE
COARSE MEDIUM FINE
SAND SIZE
SILT SIZE
CLAY SIZE
FINE GRAINED

GRAIN SIZE DISTRIBUTION
ELLIOT LAKE URANIUM TAILINGS

FIGURE 2.4


Size of opening, inches
U.S.S. Sieve size, meshes/inch
6" 3" 1½" ¾" ⅜" 4 10 20 40 60 100 200
PERCENT FINER THAN
100 90 80 70 60 50 40 30 20 10 0
GRADATION RANGE OF SLIMES FROM CUFF MINING
GRADATION RANGE OF SLIMES IN ELDORADO
GRADATION RANGE OF MIDWEST LAKE SAND TAILINGS
GRADATION RANGE OF MIDWEST LAKE SLIMES TAILINGS
LEGEND
BOREHOLE SAMPLE ELEVATION
100 10 1.0 0.1 0.01 0.001 0.0001
GRAIN SIZE, MM
COBBLE SIZE
COARSE MEDIUM FINE COARSE MEDIUM FINE SILT SIZE CLAY SIZE
GRAVEL SIZE
SAND SIZE
FINE GRAINED

GRAIN SIZE DISTRIBUTION
SASKATCHEWAN URANIUM TAILINGS

FIGURE 2.5

TABLE 2.2: SCREEN ANALYSIS OF TAILINGS COMPARING THE BULK TAILINGS AND THE FINE AND COARSE FRACTIONS AFTER SEPARATION
(Steffen, Robertson and Kirsten (B.C.) Inc., 1983)

Mesh	Micron	Bulk Tailings		Fine Tailings		Coarse Tailings	
		Cum %	Ind %	Cum %	Ind %	Cum %	Ind %
+65	210	0.04	0.04	-	-	0.12	0.12
+100	150	1.44	1.40	-	-	2.57	2.45
+150	110	7.77	6.33	-	-	14.73	12.16
+200	74	21.61	13.84	0.10	0.10	36.00	21.27
+270	53	33.37	11.76	0.28	0.18	56.46	20.40
+325	44	35.24	1.87	0.46	0.18	61.94	5.48
-325	-	100.00	64.76	100.00	99.54	100.00	38.06

Cum %- Cumulative Weight Percent
Ind % - Indicated Weight Percent

In contrast, Atterberg limit determinations carried out on samples of slimes from Cluff Lake in Saskatchewan indicated an average liquid limit of 101%, a plastic limit of 81% and an average plasticity index of about 20%. These index properties are equivalent to "inorganic silts of high compressibility and organic clays" on the plasticity chart, and suggest that these slimes will be slower to drain and more compressible than typical Elliot Lake tailings. In contrast, the sand tailings from both Elliot Lake and Saskatchewan are basically both non-plastic.

Specific Gravity

The specific gravity of Denison (Elliot Lake) slimes ranges from 2.53 to 2.80 g/cm^3 with an average of 2.67 g/cm^3, which is slightly lower than the average specific gravity of sand tailings (2.73 g/cm^3).

The specific gravity for the Cluff Lake slimes in Saskatchewan is somewhat higher, ranging from 2.96 to 3.28 g/cm^3, with an average of 3.08 g/cm^3. Knight and Haile (1983) reported a specific gravity of 2.55 g/cm^3 for the Key Lake tailings.

2.4.2 In Situ Properties

The in situ properties of tailings are significantly influenced by factors other than the index properties of the tailings. The pulp density of the discharged slurry controls the degree of particle-size segregation that will occur in a tailings basin. Lower pulp densities tend to promote a greater degree of segregation (Vick, 1983). Conversely, segregation is reduced with a thickened tailings discharge. The in situ properties are also significantly affected by whether the tailings accrete on exposed tailings beaches or in tailings ponds. Sedimentation of slimes from suspension in ponded water is by vertical settling rather than by saltation or particle rolling (Vick, 1983). Care is, therefore, necessary in extrapolating the limited data available to other situations.

The only detailed data on in situ properties such as water content and density for Canadian uranium slimes appear to be those for Elliot Lake tailings (Smyth, 1981; Golder Associates, 1984a).

Water Content

The results of water content measurements on both sand and silt tailings from Denison Mines are shown on Figure 2.6. The natural water content of the fine tailings ranges from close to 100% near the surface of the tailings to 50% at a depth of 12 m below the surface of the tailings. The natural water content of the slimes decreases noticeably with depth, due to the weight of the overlying slimes. In contrast, the water content of the coarse tailings remains relatively constant.

For the Quirke Mine slimes, the in situ water content of the tailings ranges from 30 to 105%, with an average of about 52%.

The in situ water content of Eldorado's Beaverlodge slimes from Saskatchewan ranges from 9 to 66%, with an average in situ water content of 32% (Golder Associates, 1982b). These values are much lower than would be expected based on their gradation.

In-Place Density

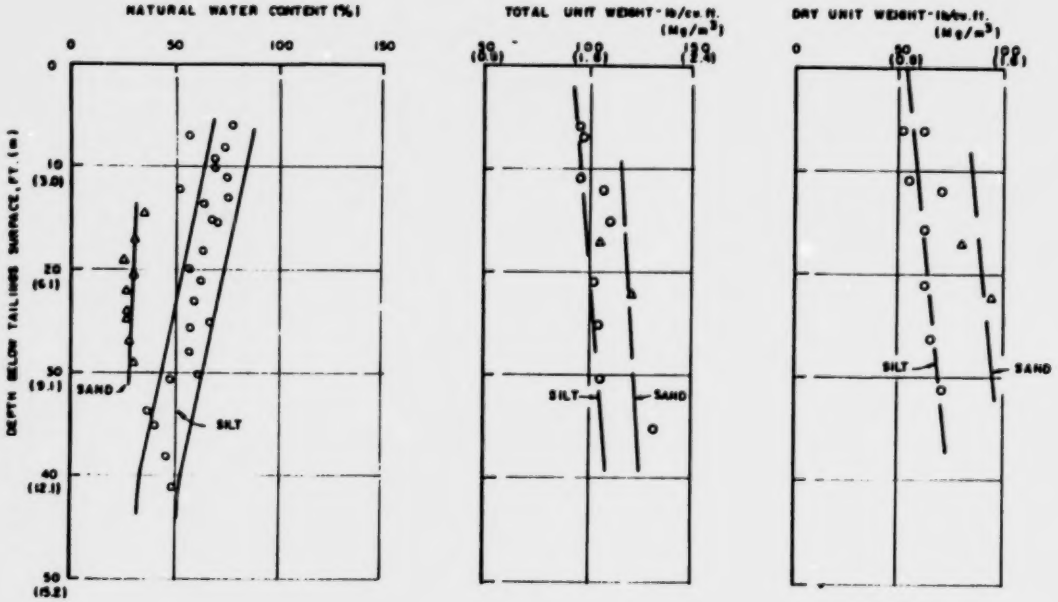
The in situ density of tailings is important both in respect to the planning of a tailings basin and the engineering behaviour of the tailings. The settled density of the tailings will control the impoundment volume required (and hence the height and volume of any tailings dams) for a given total tailings production, while the relative density (a measure of the in situ density with respect to the densest and loosest states that the material can attain in laboratory tests) has an important influence on the dynamic strength behaviour of tailings.

For Denison tailings, the total unit weight of slimes increases from 13.3 to 16.5 kN/m^3 (85 to 105 lb/cu ft), while the dry density increases from 6.3 to 10.2 kN/m^3 (40 to about 65 lb/cu ft) between the tailings surface and a depth of about 15 m (50 ft) (Figure 2.6). As shown on the same figure, the dry density of the sand tailings is generally about 40% higher than that of the silt tailings.

While the dry density of the Elliot Lake tailings sands is similar to that of copper tailings, the dry density of the uranium slimes is closer to that of gypsum tailings (see, for example, Vick, 1983). The finer fraction of the Elliot Lake tailings are needle-like

IN SITU SOIL PROPERTIES OF
SILT AND SAND TAILINGS
DENISON TAILINGS MANAGEMENT AREA
ELLIOT LAKE

FIGURE 2.6



(Colin, 1980), and this is the probable reason for the much lower densities in the slimes portion of the tailings. The removal of small proportions of sand tailings prior to discharge of a uniform slurry may, therefore, have only a negligible reduction in the overall volume required for tailings disposal.

The relative density of uranium tailings has usually been assessed from in situ tests in the tailings, such as standard penetration tests or cone penetrometer tests. Standard penetration tests provide a measure of the density of a soil by driving a standard open-ended thick steel cylinder into the ground and measuring the resistance in number of blows/0.3 m (N value).

Standard penetration tests were performed in most of the boreholes that were put down in the tailings area in Elliot Lake. The N values are plotted, in Figure 2.7, against the estimated in situ vertical effective stress (Matyas et al., 1984). The tailings slimes below the water table exhibit relatively low N values, whereas the sand tailings have moderate N values.

The relative density, D_r*, can be estimated from the N values and the effective vertical stress (see Figure 2.7). These correlations suggest that the relative density of the tailings ranges from about 0 to 50% for the tailings slimes below the water table, 0 to 70% for fine to medium sand tailings below the water table, and about 30 to 100% for sand tailings above the water table.

Fugro electric static cone penetrometer tests were also carried out to provide additional information on the geotechnical characteristics of the Elliot Lake tailings (Matyas et al., 1984). The test results are plotted in Figure 2.8, where the point resistance of the static cone is plotted against in situ vertical effective stress. As shown on Figure 2.8, a correlation between cone-bearing (relative density) and vertical effective stress exists. Interpretation of the cone resistance data suggests that most of the submerged silt slimes have extremely low relative densities.

Both the standard penetration tests and the cone penetrometer tests therefore suggest that finer silt tailings could be more susceptible to liquefaction than the coarser sand tailings. Detailed laboratory testing indicates, however, that this is not the case.

FIGURE 2.7: STANDARD PENETRATION TEST RESULTS, ELLIOT LAKE SAND AND SILT TAILINGS (MATYAS et al., 1984)

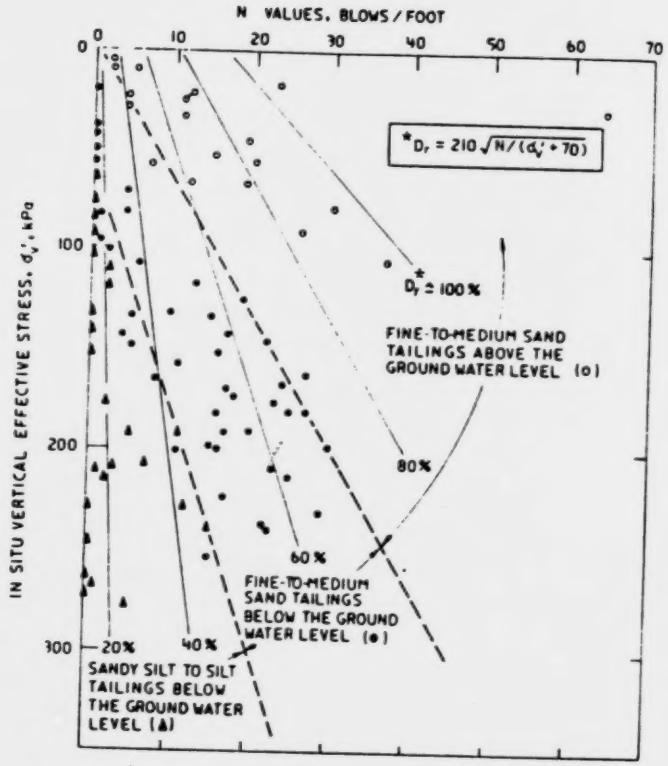
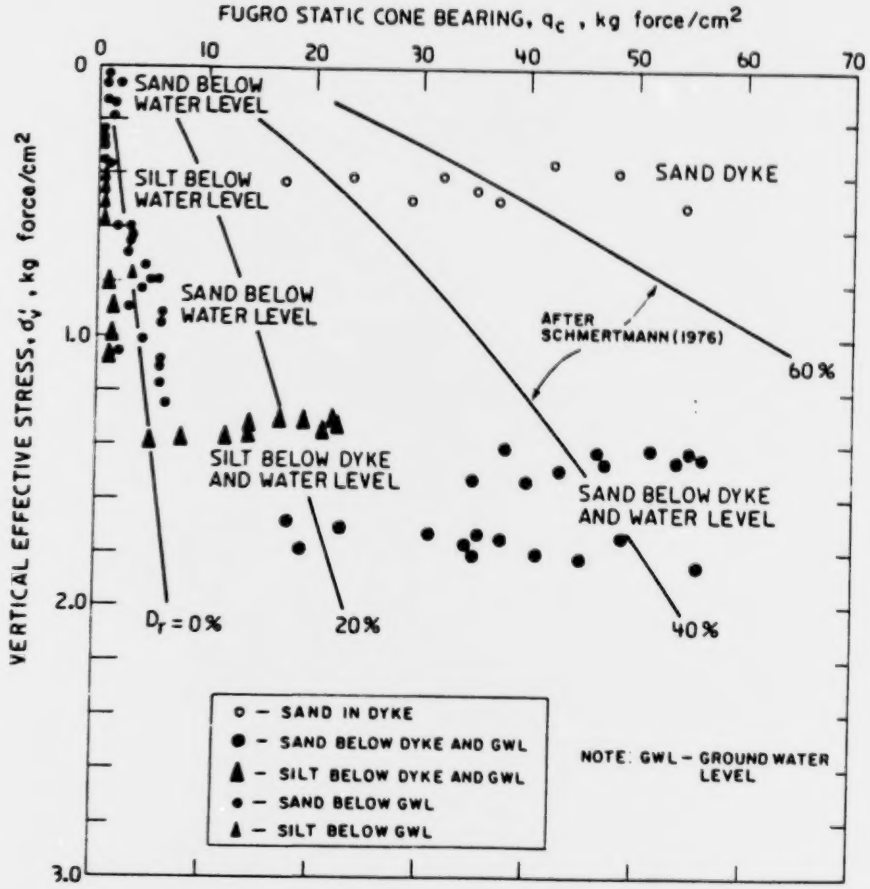


FIGURE 2.8: CONE RESISTANCE DATA AND CORRELATION WITH RELATIVE DENSITY, ELLIOT LAKE SAND AND SILT TAILINGS (MATYAS et al., 1984)



2.4.3 Engineering Properties

Engineering properties of tailings sands and slimes may differ substantially. Sand tailings generally share the engineering behaviour of loose to medium-dense deposits of natural sand. Slimes, on the other hand, are complex and may exhibit properties similar to natural silts in some cases, natural clays in other cases, or a combination of both in still others (Vick, 1983). The key parameters which will affect the overall engineering behaviour of slimes are permeabililty, consolidation behaviour (compressibility and time rate of consolidation) and both static and cyclic shear strength.

Permeability

The permeability of tailings can vary over a wide range, from 10^{-2} to 10^{-3} cm/s for clean coarse sand tailings to as low as 10^{-7} cm/s for some well-consolidated slimes.

The permeability of uniform sand deposits is often predicted by Hazen's formula:

$$k = d_{10}^2$$

where: k = coefficient of hydraulic conductivity (cm/s)
d_{10} = grain size in mm for which 10% of the particles pass by weight

Vick (1983) notes that Mittal and Morgenstern (1975) have demonstrated good correlation using the above formula for sand tailings, while Markes et al. (1977) extended its application to non-plastic slimes tailings.

Based on Hazen's formula and Figures 2.1 and 2.9, the average coefficients of hydraulic conductivity shown on Table 2.3 would be anticipated. Ranges of permeability from laboratory tests are shown on the same table and correlate well with those predicted from Hazen's formula.

The results of field permeability tests in tailings sands from Elliot Lake show good correlation with laboratory tests, but field permeability tests on tailings slimes show permeability values significantly higher than would be expected from laboratory tests. This difference can probably be attributed to the presence of coarser sandier lenses

FIGURE 2.9: HYDRAULIC CONDUCTIVITY VERSUS VOID RATIO FOR ELLIOT LAKE SAND AND SILT TAILINGS (MATYAS et al., 1984)

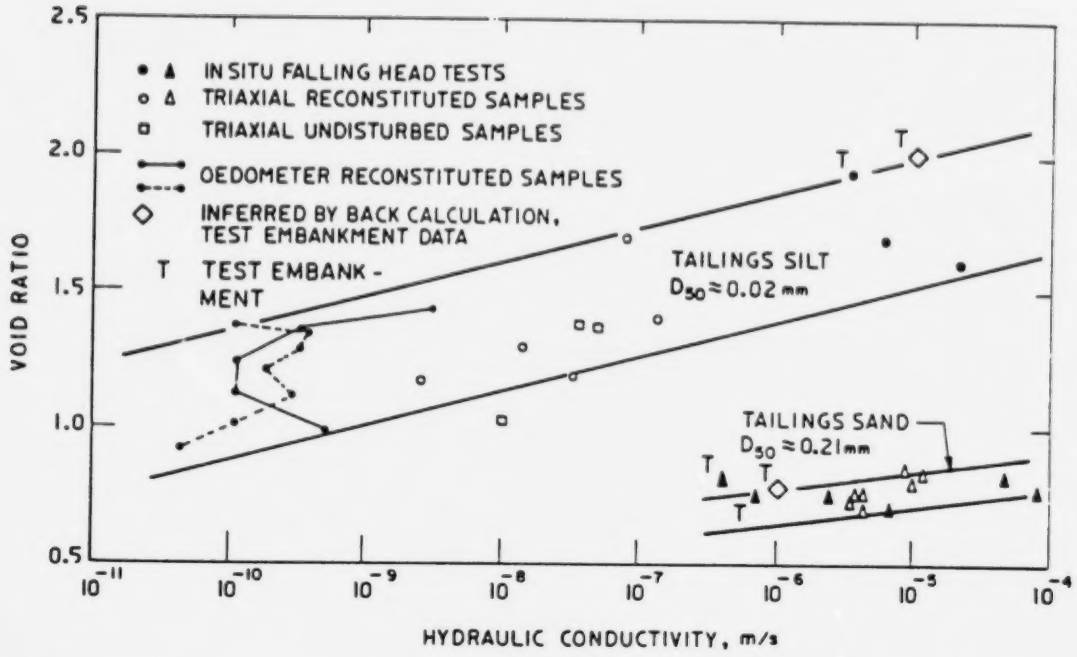


TABLE 2.3: RANGES OF HYDRAULIC CONDUCTIVITY

	Predicted from Hazen's Formula	Laboratory Tests (cm/s)	Field Tests (cm/s)	Test Embankment (cm/s)
Elliot Lake Sand Tailings	10^{-2} to 3×10^{-5}	10^{-3} to 10^{-4}	10^{-2} to 10^{-4}	10^{-4} to 3×10^{-5}
Elliot Lake Slimes Tailings	2×10^{-4} to 9×10^{-6}	10^{-5} to 10^{-8}	3×10^{-3} to 3×10^{-4}	10^{-3} to 3×10^{-4}
Midwest Lake Sand Tailings	3×10^{-4} to 6×10^{-5}	10^{-5} to 4×10^{-7}		
Midwest Lake Slimes Tailings	2×10^{-4} to 5×10^{-5}	10^{-5} to 4×10^{-8}		

within the slimes and anisotropy due to the depositional mode. The higher-than-anticipated permeabilities in the tailings slimes appear to be confirmed by the back-analysis of the rate of settlement of a test embankment across the tailings.

The above data are limited. They do, however, suggest that:

- Saskatchewan tailings, and particularly the slimes, appear to be less permeable than Elliot Lake tailings; this is considered to be due to their higher fines (clay) content; and
- actual permeabilities of slimes in the field may be significantly higher than would be anticipated from laboratory tests or on the basis of gradation; this is probably due to natural variation in the tailings and the inclusion of sand lenses in the slimes.

The permeability of a thick deposit of "pure" slimes is probably likely to be in the range of 10^{-6} to 10^{-4} cm/s. This range is one which is low compared to tailings sands, but still relatively high compared to naturally occurring clays and/or synthetic liner materials.

Compressibility

Tailings are often deposited in a relatively loose saturated depositional state. They are also often uniform in gradation and of high angularity. Because of these factors, both tailings sands and slimes are more compressible than natural soils of similar type. Since tailings are generally deposited into water or on tailings beaches where the phreatic surface is close to, or at the surface of the tailings, tailings are usually normally-consolidated, i.e., they have not been subjected to excess additional past loading. The only way that slimes deposits may become over-consolidated is by desiccation or capillary suction on exposed, above-water deposits.

Vick (1983) reviewed the compressibility of various tailings and concluded that for sand tailings, the compression index, C_c, usually ranges from 0.05 to 0.10, while slimes of low plasticity show C_c values ranging from 0.20 to 0.30, about three to four times higher than values for sands.

The only published data for Canadian uranium tailings is that from Elliot Lake (Golder Associates, 1980; Matyas et al., 1984). The consolidation behaviour of uranium slimes was measured in conventional oedometer tests on piston samples obtained from the Denison Mines Tailings Management Area. They were found to be relatively compressible with a compression index of between 0.2 and 0.3.

The consolidation behaviour of sand tailings from Denison's Tailings Management Area was also examined by oedometer tests on two reconstituted samples. The test data indicated that those sand tailings are relatively incompressible, with an average coefficient of compression, C_c, of 0.04.

Matyas et al. (1984) summarized the consolidation test results on Denison and Quirke sand and slimes uranium tailings from Elliot Lake (see Figure 2.10). All of the above values are in broad agreement with those for different types of tailings summarized by Vick (1983). These suggest that uranium tailings are no different from other tailings in this regard. Settlements under any imposed loading will be much higher over slimes than sand tailings. It would, therefore, be very difficult to construct a cover/cap across slimes without inducing large settlements (probably in the order of a metre or more), whereas settlements above sand tailings would be modest.

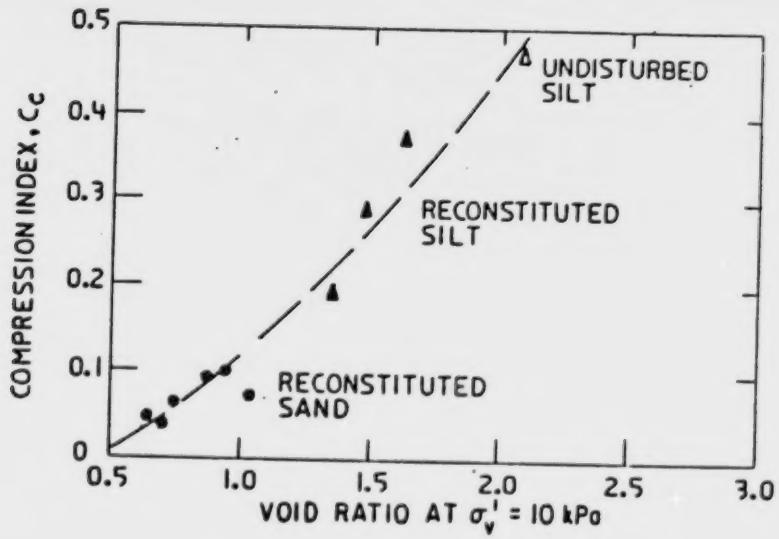
Time for Consolidation

The time which materials take to consolidate can have important effects on their overall behaviour. Vick (1983) noted that primary consolidation occurs so rapidly in sand tailings that it is difficult to measure in the laboratory (coefficients of consolidation, C_v, of 5×10^{-1} to 10^{2} cm^2/s), while the coefficient of consolidation for slimes is similar to natural clays, varying from 10^{-2} to 10^{-4} cm^2/s.

Data from Elliot Lake uranium tailings (Golder Associates, 1980) fall towards the low end of the above ranges. Tests on Elliot Lake slimes indicated coefficients of consolidation varying from 5×10^{-4} to 2×10^{-3} cm^2/s, compared to values of 5×10^{-2} to 2×10^{-1} cm^2/s for Elliot Lake sand tailings.

The slow time for consolidation is also apparent from the observation of excess pore pressures in the tailings slimes at the Denison site when the rate of accretion of tailings slimes was relatively rapid (Matyas et al., 1984).

FIGURE 2.10: VARIATION OF COMPRESSION INDEX WITH INITIAL VOID RATIO FOR ELLIOT LAKE SAND AND SILT TAILINGS (MATYAS et al., 1984)



Data from the Key Lake tailings (Knight and Piesold, 1985) do not indicate data for both slimes and sands. But the bulk values for C_v are in the range of $5x10^{-2}$ to $3x10^{-2}$ cm^2/s that correspond to values for slimes from Elliot Lake (Table 2.4). With about 70% less than 200 mesh particles and greater quantities of chemical precipitates, this behaviour is not surprising. It is expected that if these tailings were segregated into coarse and fine fractions, consolidation would become much slower with values for C_v approaching those of clays.

The effect of enhanced slimes contents on the magnitude of settlement and time over which settlements occur may, therefore, be significant.

Shear Strength

The strength of a soil may be evaluated under three conditions:

- the static drained shear strength, which will apply under conditions of slow loading, in which there are no excess pore pressures;
- the undrained shear strength, which will apply under conditions of fast loading in which there is no time for excess pore pressure to drain; this is important in evaluating the flow-like behaviour exhibited by many tailings deposit failures; and
- the cyclic strength, which will apply in the event of seismic shaking due to an earthquake.

The strength of uranium tailings under these three conditions is discussed below.

o Drained Shear Strength

Despite their loose depositional state, tailings generally have high drained shear strengths (effective friction angles of 30 to 40 degrees), primarily due to their high degree of angularity. Matyas et al. (1984) summarized data from Elliot Lake sand and slimes (see Figure 2.11). The Elliot Lake tailings are cohesionless and data indicate little difference between sand and slimes tailings. Even slimes tailings with high void ratios demonstrate effective friction angles of 37 degrees or higher.

TABLE 2.4: COEFFICIENTS OF CONSOLIDATION, COMPRESSIBILITY AND PERMEABILITY OF BULK TAILINGS FROM KEY LAKE, SASKATCHEWAN (data from Knight and Piesold, 1985)

C_v (m^2a^{-1})	M_v ($m^2\,kN^{-1}$)	K (calc) (ms^{-1})
52.7 ($1.7x10^{-2}$)*	0.00031	$5x10^{-9}$
102 ($3.2x10^{-2}$)	0.00015	$4x10^{-9}$
37.7 ($1.2x10^{-2}$)	0.0019	$2.2x10^{-8}$
64.9 ($2.06x10^{-2}$)	0.0014	$2.8x10^{-8}$
41.2 ($1.3x10^{-2}$)	0.00059	$7x10^{-9}$
15.5 ($4.9x10^{-3}$)	0.00034	$1x10^{-9}$

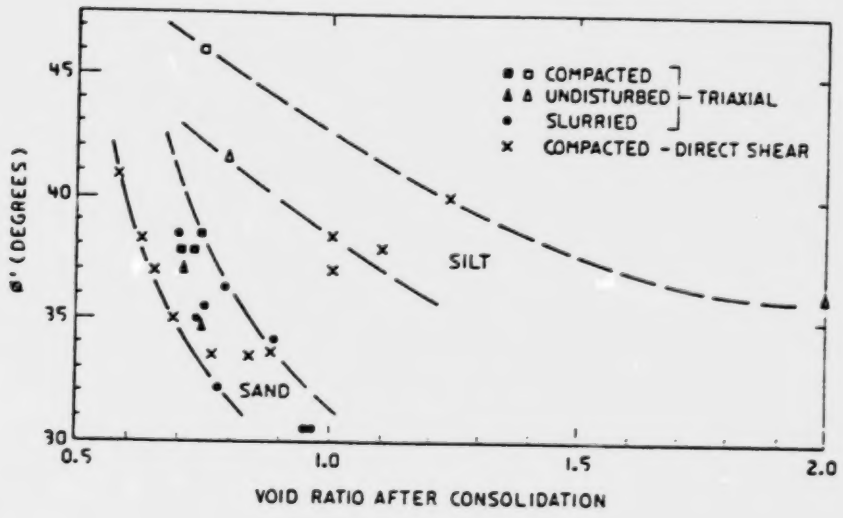
C_v = coefficient of consolidation.

M_v = coefficient of compressibillity.

K = coefficient of permeability (hydraulic conductivity).

* = numbers in brackets in units of $cm^2 \cdot s^{-1}$.

FIGURE 2.11: SHEAR STRENGTH DATA FOR ELLIOT LAKE SAND AND SILT TAILINGS (MATYAS et al., 1984)



o Undrained Shear Strength

Vick (1983) summarized the limited data available on the undrained shear strength of various tailings materials. Vick concluded that vane tests are often difficult to interpret in tailings slimes, since the test represents conditions that are neither fully drained nor fully undrained.

The only data available for this study are those from in situ vane tests in the Denison Mines Tailings Area. Here, the undrained shear strength increased to between 4.8 and 14.4 kPa (100 and 300 lb/sq ft) below a depth of about 3 m (10 ft). These values are lower than those quoted for other types of tailings by Vick, but the reason is not apparent.

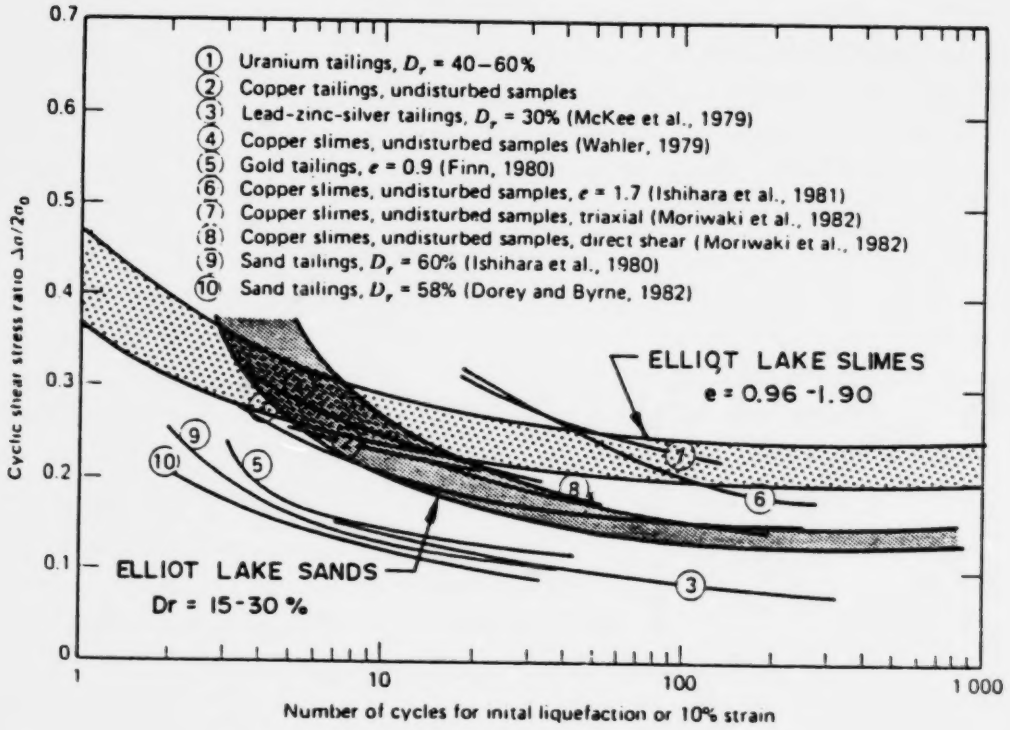
o Cyclic Shear Strength

The seismic risk in the central part of Canada (Saskatchewan, Manitoba, northwestern Ontario) is low to negligible. This risk is greater, however, in parts of the Maritimes, Quebec, eastern Ontario and British Columbia. Cyclic triaxial test data on Canadian uranium mine tailings are, therefore, very limited and only one study is known to have been reported. Tests were carried out on both sand and slimes tailings from Elliot Lake by Professor Silver at the University of Chicago. Eight samples of tailings slimes were tested at their natural density ranging from 6.3 to 13.8 kN/m^3 (40 to 88 lb/cu ft). Tests on tailings sands were carried out on both undisturbed and reconstituted samples; the results are plotted in Figure 2.12. The test results for uranium tailings indicate that, at between 6 and 8 cycles of loading (equivalent to a magnitude 6.5 earthquake), the dynamic strength of the slimes is essentially the same as that of the sand tailings. The results are also in agreement with those of Vick (1983) who noted that "slimes tailings overall have generally higher cyclic shear strength than do sands or undifferentiated tailings". Earlier, it might have been anticipated that the cyclic shear strength of looser slimes tailings with extremely low relative densities would have been lower than that of tailings sands.

2.4.4 Overall Behaviour

The slope at which tailings are deposited and the potential for liquefaction due to earthquake ground motions are two aspects of overall engineering behaviour which cannot be measured uniquely in the laboratory.

FIGURE 2.12: CYCLIC SHEAR STRENGTH FOR ELLIOT LAKE SAND AND SILT TAILINGS (GOLDERS DATA) AND OTHER TAILINGS (VICK, 1983)


1 Uranium tailings, D_r = 40–60%
2 Copper tailings, undisturbed samples
3 Lead-zinc-silver tailings, D_r = 30% (McKee et al., 1979)
4 Copper slimes, undisturbed samples (Wahler, 1979)
5 Gold tailings, e = 0.9 (Finn, 1980)
6 Copper slimes, undisturbed samples, e = 1.7 (Ishihara et al., 1981)
7 Copper slimes, undisturbed samples, triaxial (Moriwaki et al., 1982)
8 Copper slimes, undisturbed samples, direct shear (Moriwaki et al., 1982)
9 Sand tailings, D_r = 60% (Ishihara et al., 1980)
10 Sand tailings, D_r = 58% (Dorey and Byrne, 1982)
ELLIQT LAKE SLIMES
e = 0.96 -1.90
ELLIOT LAKE SANDS
Dr = 15-30 %
Cyclic shear stress ratio $\Delta\sigma/2\sigma_0$
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
10
100
1 000
Number of cycles for inital liquefaction or 10% strain

Slope of Deposition

The transportation and deposition of tailings is a complex process that is influenced by many factors, such as solids content of the slurry, grain shape, size, distribution, specific gravity, temperature and distance of travel.

When tailings are discharged at lower pulp densities, they are transported by gravity in a stream, which meanders on the surface of the beach and essentially terminates at the tailings pond. Coarse particles are deposited near the discharge pipe whereas the finer particles are carried into the pond. However, the degree of segregation of particles is still dependent on the length of the beach. On a short beach (100 m), relatively little segregation will occur. On a long beach (1,000 m), continuous segregation takes place as the tailings flow over the beach (see Matyas et al., 1984).

One of the best documented examples of the variation in the slope of deposition of hydraulically deposited tailings is that of the Denison Mines Tailings Management Area. Coarser tailings are deposited at an approximate slope of 1.4% within 150 m (500 ft) to 300 m (1,000 ft) of the discharge, then at 0.6 to 0.7% between 230 m (750 ft) and 1,520 m (5,000 ft) from the discharge point and, finally, the finest tailings at a slope of only about 0.3% between 1,520 m (5,000 ft) and 2,440 m (8,000) ft) from the discharge point. This latter area is inundated during raising of the headpond.

Blight and Bentel (1983) suggested that the variation in slope is due to the fact that the coarser material, which settles out first, drains rapidly and develops shear strength faster than the finer material which settles out slowly further down the beach and drains more slowly.

Enhanced slimes contents may, therefore, lead to flatter tailings slopes and, consequently, these will tend to drain less readily after deposition has been completed than tailings with higher sand contents deposited at steeper slopes.

Liquefaction Potential

The potential for liquefaction of any deposit subjected to earthquake shaking may be evaluated by two basic methods:

1. Using empirical methods based on field observations of the performance of similar deposits in previous earthquakes. This might involve the use of in situ characteristics of the deposits (e.g., standard penetration test results) to determine similarities or dissimilarities between these sites and the proposed new site with regard to their potential liquefaction behaviour.
2. Using methods based on an evaluation of the cyclic stress or strain conditions likely to be developed in the field by a design earthquake and comparing these stresses or strains with those observed to cause liquefaction of representative samples of the deposit in appropriate laboratory tests which provide an adequate simulation of field conditions, or which can provide results permitting an assessment of the soil behaviour under field conditions.

An example of the empirical approach was given by Seed (1979), who utilized penetration resistance tests to infer material behaviour during the Niigata earthquake in Japan. Another method, which utilizes the penetration resistance values and grain size distribution and developed by Japanese engineers, was reported by Sherif and Ishibashi (1978).

Such empirical charts have several limitations. For example, the boundary between zones of inferred material behaviour are rather poorly defined (especially for silty materials such as mine tailings). In addition, this type of approach does not take into account the parameters controlling ground motions such as duration, magnitude, predominant frequency, etc.

Seed et al. (1983) presented a new empirical method whereby standard penetration test results can be used to evaluate liquefaction potential. This method also takes into account the duration, magnitude and frequency of ground motions. With this method, values of stress ratio τ/σ'_v known to be associated with some evidence of liquefaction or no liquefaction in the field can be plotted as a function of the normalized penetration resistance of the deposit involved.

Matyas et al. (1984) used Seed et al.'s semi-empirical method to assess the possibility of liquefaction of uranium tailings in Elliot Lake. They concluded that localized zones within the tailings deposit would be susceptible to liquefaction.

More rigorous analyses on Elliot Lake uranium tailings were carried out by Conlin (1981). As noted by Matyas et al. (1984), he concluded that material instability, due to seismically induced liquefaction, was unlikely.

Although the evaluation of liquefaction potential of tailings at a site with moderate seismicity is extremely complex, it appears that tailings are not as susceptible to liquefaction as their generally loose state and low relative density would suggest. It may also be relevant to note that Seed et al. (1983) presented evidence that silty sands are considerably less vulnerable to liquefaction than clean sands. This is in agreement with Vick (1983) who, as noted earlier, concluded that "slimes tailings overall have generally higher cyclic shear strength than do sands or undifferentiated tailings".

Although the use of slime-enhanced tailings in potentially seismically active areas will always have to be carefully evaluated, it is concluded that slimes are probably less susceptible to liquefaction than coarser tailings.

2.5 Geochemical Properties

The data in this section have been derived largely from studies on tailings from the Elliot Lake uranium district. Investigations have included components of pore water chemistry and solids chemistry and mineralogy. Data from Saskatchewan uranium tailings are either scarce or non-existent. Because many tailings deposits operating in Saskatchewan are relatively recent, most pertinent information has been derived from process development studies. Studies are currently being conducted to characterize both the tailings from the classic, vein-type deposits (i.e., Gunnar) and from the high-grade unconformity deposits (i.e., Key Lake), but as yet only preliminary results are available for the Key Lake tailings deposit (G. Feasby, pers. comm., 1985). Existing data are summarized in Table 2.1.

2.5.1 Mineralogy

The mineralogical composition of uranium mill tailings depends on the original composition of the ores, as well as the treatment performed in the mill circuit. The two major uranium ore types presently mined in Canada are represented by the Elliot Lake variety at the Denison and Quirke Lake operations and by the Saskatchewan variety at the Key Lake and Rabbit Lake properties. Although the alkaline milling process has been used in one operation in the past (Beaverlodge), the standard uranium extraction process consists of a sulphuric acid leach with limestone/lime neutralization prior to discharge.

Some solids dissolve during milling and other solids precipitate during the subsequent neutralization of the mill leach solution. These secondary solids (precipitates) consist primarily of gypsum ($CaSO_4.2H_2O$) and aluminum and ferric hydroxides ($Al(OH)_3$, $Fe(OH)_3$). Lists of primary and secondary minerals associated with the two major ore types are given in Tables 2.5a and 2.5b.

In most cases, the range of primary ore minerals will be subjected to similar grinding and therefore most minerals will occur at the same relative concentrations in the coarse and fine-grained fractions of the tailings. Segregation may occur when some softer minerals achieve a finer grind and are, therefore, relatively more concentrated in the fine fraction. In contrast, more reactive minerals that tend to dissolve in the mill leach circuit could be somewhat concentrated in the coarse fraction because the fine-grained particles will dissolve more rapidly than the coarse-grain ones.

By nature, the secondary minerals that are formed by precipitation in the mill are fine grained and will be concentrated in the fine-grained fraction of the tailings.

The segregation of minerals with grain size is most obvious for gypsum. The distribution of gypsum in a fresh Quirke Lake tailings sample is given in Figure 2.13. The data for this sample show that, although only about 10% of the total solids have a grain size less than 45 microns, about 70% of the gypsum occurs in this fine-grained fraction (Cherry et al., 1982). Some segregation is also evident for reduced sulphur (as pyrite) and carbonate (as calcite) which both exhibit some concentration in the fine-grained material. In general, however, the sulphur and carbonate distributions parallel that of the total solids whereas that of gypsum is markedly different.

TABLE 2.5a: SUMMARY OF MAJOR MINERALS FOUND IN TYPICAL URANIUM ORES AND TAILINGS FROM ELLIOT LAKE (from BEAK, 1985a)

Primary Constituents	Composition (mol/tonne)	Secondary Constituents (Formed in Mill)	Composition (mol/tonne)
SiO_2	10,900	$Fe(OH)_3(s)$	25
Sericite	400	$Al(OH)_3(s)$	29
Fe (as sulphide)	530	K (in pore water)	11
S (with Fe)	780	Gypsum	460
K_2O	24	$CaCO_3(s)$	18
Ba	1.6	$SiO_2(am)$	6
Pb	1.5	$SrSO_4$	0.014
Sr	-	$PbSO_4$	0.07
		$BaSO_4$	0.0005

Assumptions:

1. Based upon Rio Algom ores.

2. Solid:liquid ratio in leaching pachucas is 2.62 g solid/g liquid 1:1, vol/vol.

3. Concentrations of cations in leaching liquor in pachucas are assumed to define the magnitude of secondary minerals formed. The leaching liquor concentrations from BEAK (1985) are: Fe: 4,100 mg/L (±480; n = 14); Al: 2,300 mg/L (±840, n = 14); Ba: 0.2 mg/L; K: 1,250 mg/L (±395, n = 14); Pb: 45 mg/L (±4.4, n = 14); SiO_2: 1,030 mg/L (±121, n = 12); Sr: 3.4 mg/L (±0.25, n = 13). Gypsum concentration is based upon sulphate concentration and mill mass balance (BEAK, 1982) and is 500 mol/tonne ore.

4. Composition of primary constituents is based upon ore composition minus the portion leached into solution in the leaching pachucas. Addition of gypsum and calcite increase ore mass by 8.7%. It is assumed that leaching processes act on the ore conservatively (i.e., that uranium extraction has a minimal effect upon the ore mass and that the material leached from the original ore mass becomes secondary precipitates in the tailings). The mass added as iron balls is assumed negligible. Accordingly, ore composition, gypsum and calcite are adjusted by 1.087 to account for the additional mass.

5. These data differ from data used in other sections of the report. The values in Chapter 6 (FeS_2: 415 mol/tonne; gypsum: 500 mol/tonne; calcite: 110 mol/tonne) are based on 5% pyrite (rather than 6.4% FeS) and a design addition of calcite. The values of Chapter 10 (FeS_2: 416 mol/t; $Fe(OH)_3$(am): 305 mol/t; gibbsite: 204 mol/t; gypsum: 555 mol/t; and calcite: 20 mol/t) are based upon:

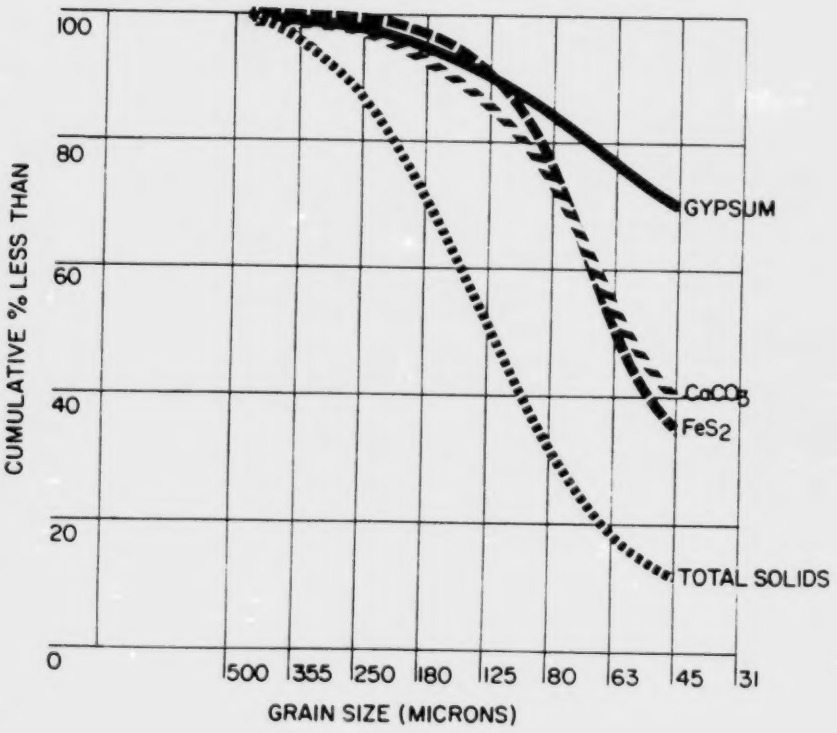
   - assumed mill concentrations of Fe = 10,200 mg/L, Al = 3,900 mg/L, total sulphate = 32,000 mg/L and a S:L ratio of 6:10, and
   - assumed tailings concentration of FeS_2 (5%) and $CaCO_3$ (0.2%).

TABLE 2.5b: ESTIMATE OF MAJOR MINERALS FOUND IN KEY LAKE LAYERED URANIUM TAILINGS (from Knight and Piesold, 1985)

Mineral/Compound	Formula	Weight (%)
Major Constituents		
Quartz	SiO_2	48
Gypsum	$CaSO_4.2H_2O(2CaSO_4.H_2O)$	26
Graphite*	C	2
Illite, Trichlorite	(K, Al, Mg, Si, Ti, O, OH, Al, Mg, Si, O, OH)	7.4
Ettringite	$Ca_6Al_2(SO_4)_3(OH)_{12}.26H_2O$	3.7
Calcium Arsenate*	$Ca_3(AsO_4)_2.3H_2O$	2.0
Calcite*	$CaCO_3$	5.0
Gersdorffite	NiAsS	0.8
Nickel Compounds	NiS, $Ni(OH)_2$ Ni,FeS_2	2.0
Iron Compounds	Fe_2O_3,FeS_2,$Fe(OH)_3$	3.2
Minor Constituents		
Cobalt Compounds*	CoS,$Co(OH)_2$	0.1
Uranium Compounds	U(adsorbed), hydrated oxides	0.1
Zinc Compounds	ZnS, ZnFeS, $Zn(OH)_2$	0.1
Lead Compounds	PbS, $Pb(OH)_2$	0.1
Copper Compounds	CuS, $Cu(OH)_2$	0.1
TOTAL		100.2%

* Assumed, no measurements available.

FIGURE 2.13: GRAIN SIZE VS. CUMULATIVE DISTRIBUTION OF TOTAL SOLIDS, GYPSUM, CARBONATE ($CaCO_3$) AND PYRITE (FeS_2) CONTENTS FOR ONE SAMPLE OF FRESH QUIRKE LAKE TAILINGS
(data from Cherry et al., 1982)



Mineralogical segregation has also been observed in tailings from existing deposits. Samples from the Williams Lake and Stanrock tailings deposits show increasing concentrations of solid carbonate (as calcite), sulphate (as gypsum) and leachable iron (as $Fe(OH)_3$), along with an increasing cation-exchange capacity, and with decreasing grain size as shown in Figure 2.14 (Feenstra et al., 1982). These tailings in general were not highly weathered and may be fairly representative of the tailings at the time of discharge. The leachable iron content here would represent the ferric oxyhydroxide material that precipitates in the mill or that forms later in the tailings deposit. Cation exchange capacity (CEC) is a measure of the potential exchange sites for adsorbed cations on the solids surfaces. Because this parameter is dependent upon the total surface area available and because the total area per unit mass increases with decreasing grain size, it is reasonable that the CEC increases in the observed manner. The segregation of sulphate is also evident in other weathered tailings samples as shown in Figures 2.15 and 2.16.

Indirect evidence for segregation is also available. Bench-scale milling and uranium extraction tests have been performed on high-grade ores from Saskatchewan (Sherritt, 1980). During the acid leach procedure, it was found that up to 80% of the Ni and As in the ore was dissolved. Analysis of the solids before and after leaching revealed that the Ni and As were preferentially concentrated in the fine-grained fraction of the tailings. This concentration in the fines occurs because the As and Ni are first dissolved then reprecipitated in the mill process.

Data from another mine in Saskatchewan shows that sulphate, reduced sulphur and carbonate are all concentrated in the finer-grained fraction (Table 2.6a). In contrast, samples of Key Lake tailings that were segregated to obtain the grain size fraction of less than five microns showed very little apparent mineralogical segregation from the bulk tailings (Table 2.6b). This latter analysis represents an XRD study and, therefore, may not be strictly comparable to the chemical analysis reported above.

2.5.2 Radionuclides

A number of radionuclides are present in the tailings at concentrations that pose a potential threat to the environment. Although Th-232 and its daughters are more abundant in Elliot Lake tailings than in those from Saskatchewan, the suite of radioactive elements is consistent between the two ore types.

FIGURE 2.14: RELATIONSHIPS BETWEEN THE CHEMICAL COMPOSITION OF THE TAILINGS SOLIDS AND MEAN GRAIN SIZE FOR SAMPLES FROM WILLIAMS LAKE TAILING MANAGEMENT AREA, ELLIOT LAKE (FEENSTRA et al., 1982; LINES BASED ON VISUAL FIT)

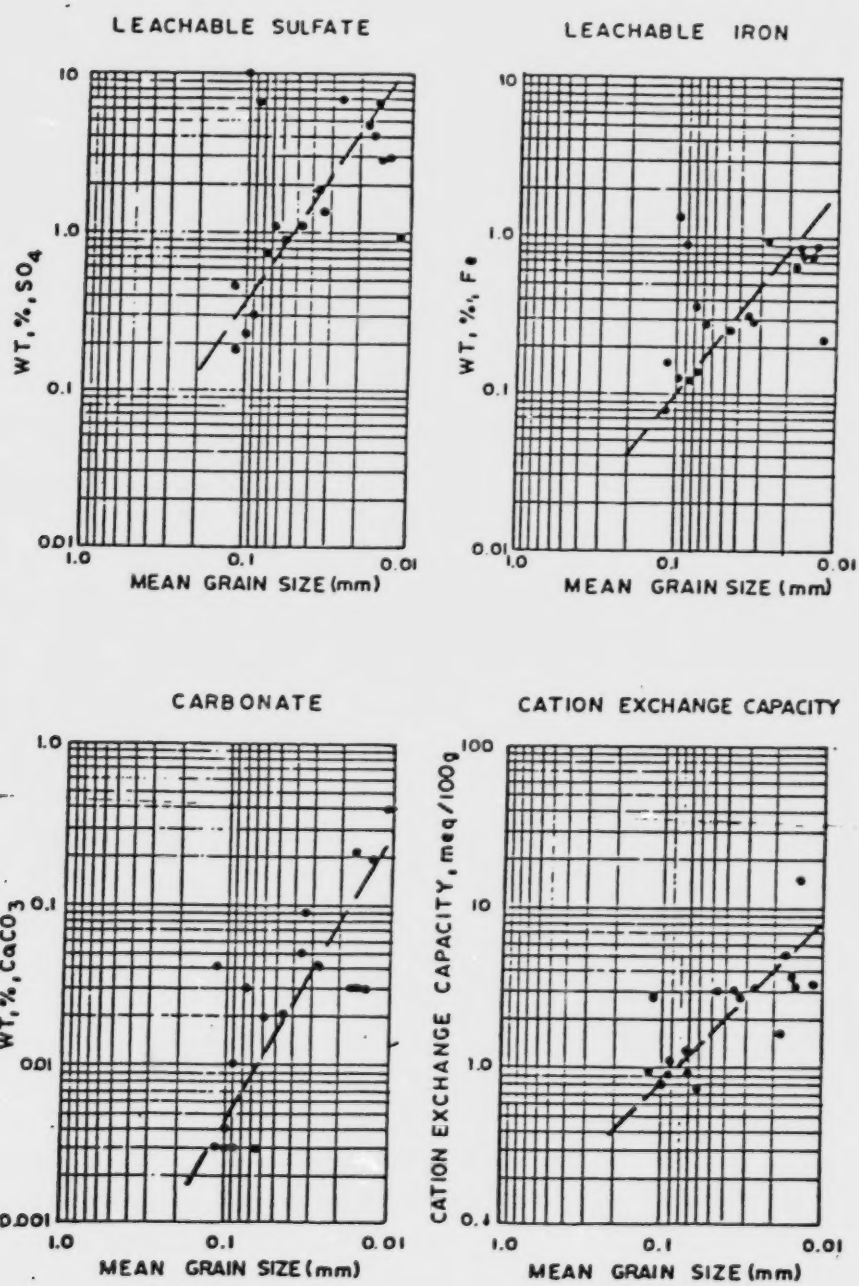


FIGURE 2.15: RELATIONSHIPS BETWEEN GYPSUM CONTENT AND MEAN GRAIN SIZE FOR WEATHERED TAILINGS FROM THE NORDIC MAIN TAILINGS MANAGEMENT AREA, ELLIOT LAKE (DATA FROM SMYTH, 1981)

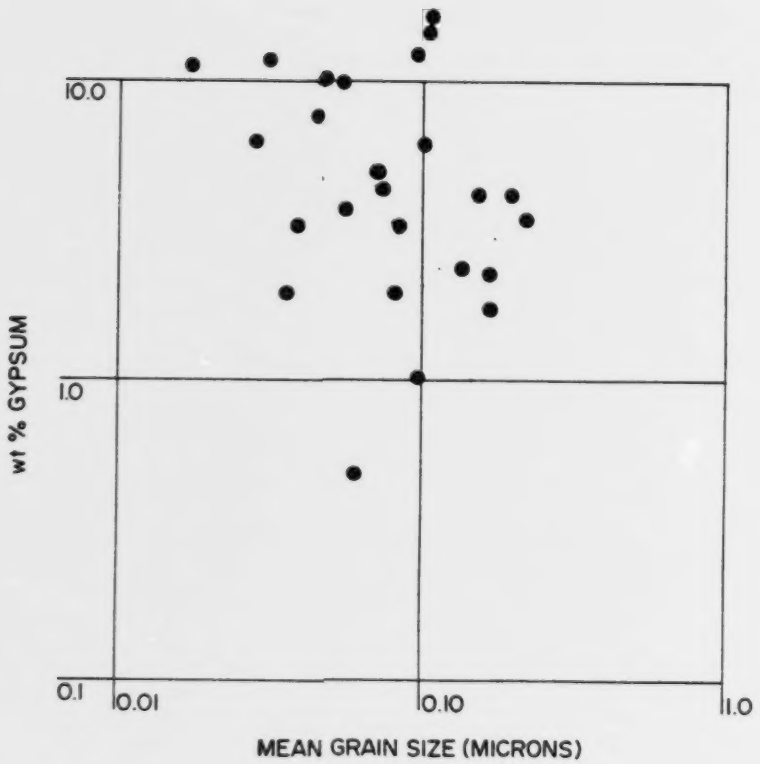


FIGURE 2.16: VARIATION OF SULPHATE CONTENT (GYPSUM) WITH THE FRACTION OF FINES IN WEATHERED TAILINGS FROM ELLIOT LAKE (DATA FROM MURRAY AND MELLIS, 1973; LINE BASED ON VISUAL FIT)

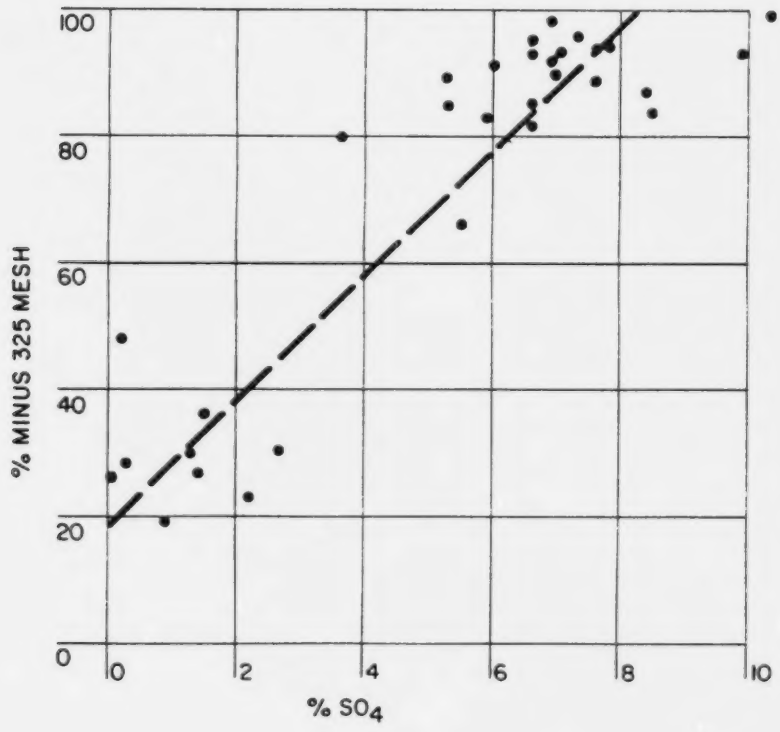


TABLE 2.6a: COMPARISON OF SULPHATE, TOTAL REDUCED SULPHUR AND CARBONATE CONTENTS FOR SAND AND SLIME FRACTIONS FROM URANIUM TAILINGS IN NORTHERN SASKATCHEWAN

	Sandy Fraction*	Slimes
Sulphate (%)	0.04 to 0.87 (0.37)	1.0 to 3.0 (2.2)
Total Sulphur (%)	0.04 to 0.60 (0.18)	0.61 to 1.14 (0.87)
Carbonate (%)	LT 0.1 to 0.4 (?)	0.5 to 11.5 (4.9)

* Ranges of values with geometric means in brackets.

TABLE 2.6b: MINERALOGICAL COMPOSITION OF LESS THAN 5 MICRON GRAIN-SIZE FRACTION COMPARED TO THAT OF BULK TAILINGS. ESTIMATES BY XRD (data from Knight and Piesold, 1985)

Mineral	Minus Five* Micron Size	Bulk Tailings
Quartz	65	48
Gypsum	20	26
Ettringite	5	4
Illite	5	7**
Trichlorite	5	

* Average of two samples - the minus 5 micron fraction comprises about 18% by weight of the total sample.

** Sum of illite and trichlorite given.

A list of radionuclides of concern is presented in Table 2.7. Although the assemblage of major minerals in the ore is relatively well known, the actual occurrence of solids containing radionuclides and many metals is not well defined. This poses some difficulty in predicting the solubility of the various species of concern. Nonetheless, some correlations with grain size have been observed for certain radionuclides.

The distribution of Ra-226 is the most outstanding example of segregation of radionuclides with grain size. In a study of radium concentrations in Elliot Lake tailings, Skeaff (1976) found that up to 90% of the Ra-226 occurred in the less than 200 mesh fraction (less than 75 micron diameter particles) as shown in Figure 2.17.

Similar findings were reported by Kaiman (1977) in a study of weathered mill tailings from Elliot Lake (see Table 2.8). This correlation reflects the probable surface control on radium concentration either by adsorption or coprecipitation mechanisms in the mill leach circuit and in tailings deposits (IEC BEAK, 1985b). Because the fine-grained particles represent the greater portion of surface area, it is not unreasonable that radium is associated with this grain-size fraction.

There is no evidence for segregation of Ra-226 in tailings from high-grade ores from Saskatchewan (i.e., Key Lake). However, based on a composite concentration of about 6,200 pCi/g and a 90% occurrence of this nuclide in the fine fraction, the concentration in the slimes could be on the order of 9,000 pCi/g or greater.

The concentrations of Pb-210 in the solids appear to parallel those of radium. The evidence is scarce, however, and is based on trends with grain-size for shallow-depth samples collected in the Nordic main tailings by Smyth (1981). The plot in Figure 2.18 shows the relationship between grain size and both Ra-226 and Pb-210 contents. The correlation (r) between the concentrations of the two radionuclides is 0.91. A plot of Ra-226 versus Pb-210 for these samples is given in Figure 2.19. Therefore, it is reasonably certain that Ra-226 and Pb-210 will be relatively concentrated in a slime-enriched fraction of uranium tailings.

There does not appear to be any evidence for grain-size segregation of other radionuclides. Although the data are scarce, two studies of weathered Elliot Lake tailings (Kaiman, 1977; Moffett and Tellier, 1978) suggested that there may be some

TABLE 2.7: RADIONUCLIDES OF CONCERN IN URANIUM MILL TAILINGS

Isotope	Half-Life	Emission
Ra-226	1,620 a	Alpha
Pb-210	22 a	Beta
Po-210	140 d	Alpha
Th-230	8×10^4 a	Alpha
Th-234	24.1 d	Beta
U-234	2.5×10^5 a	Alpha
U-238	4.5×10^9 a	Alpha
Rn-222	3.8 d	Alpha

FIGURE 2.17: CUMULATIVE DISTRIBUTION OF TOTAL SOLIDS AND Ra-226 IN FRESH TAILINGS FROM ELLIOT LAKE (MODIFIED FROM SKEAFF, 1976)

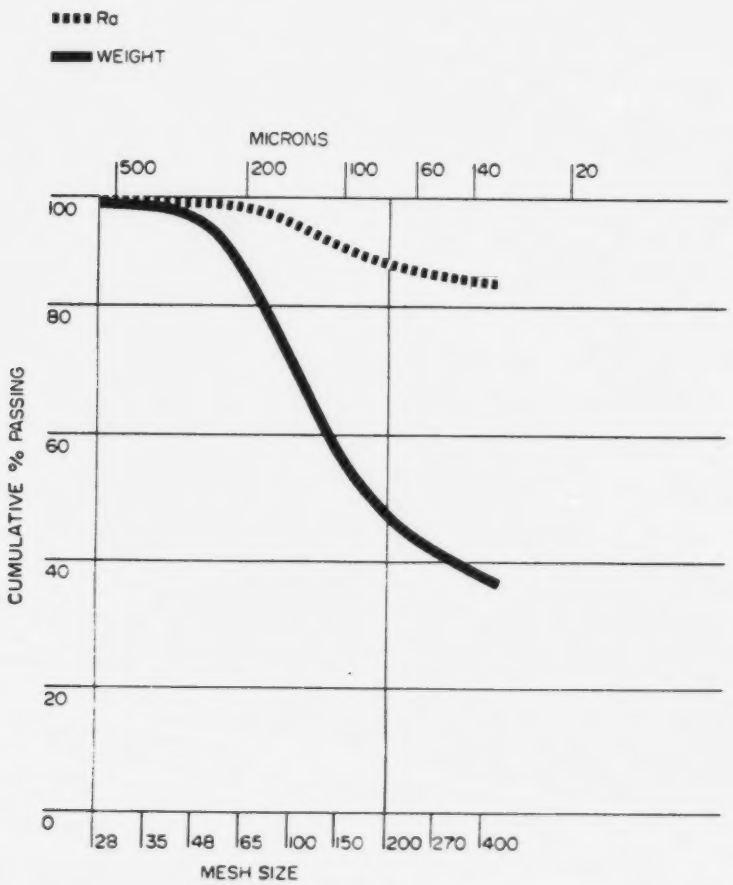


TABLE 2.8: RADIUM DISTRIBUTION IN TAILINGS (from Kaiman, 1977)

Mesh Size	Weight Percent Solids	Ra (pCi/g)	Ra Distribution (%)
+100	6.7	88.2	2.1
-100+150	12.5	82.6	3.7
-150+200	12.5	77.6	3.5
-200+325	12.0	85.1	3.7
-325	53.5	425	87.0*
Loss*	2.8		
	100.0		100.0

* Assumes loss is all minus 325-mesh.

FIGURE 2.18: RELATIONSHIP BETWEEN MEAN GRAIN SIZE AND TWO RADIONUCLIDES (Pb-210 AND Ra-226) IN WEATHERED TAILINGS SOLIDS FROM THE NORDIC MAIN TAILINGS MANAGEMENT AREA, ELLIOT LAKE (DATA FROM SMYTH, 1981)

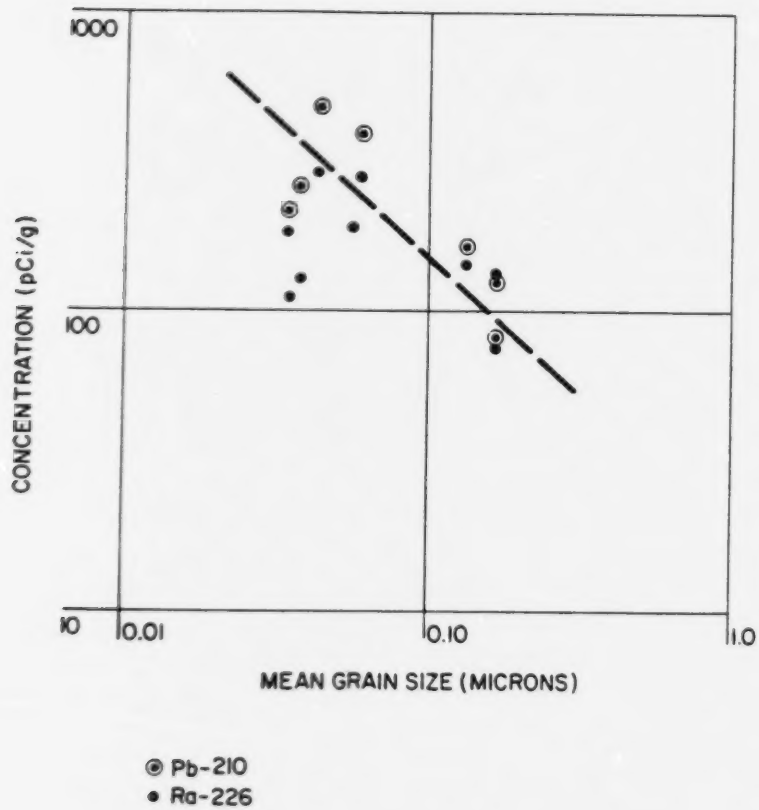
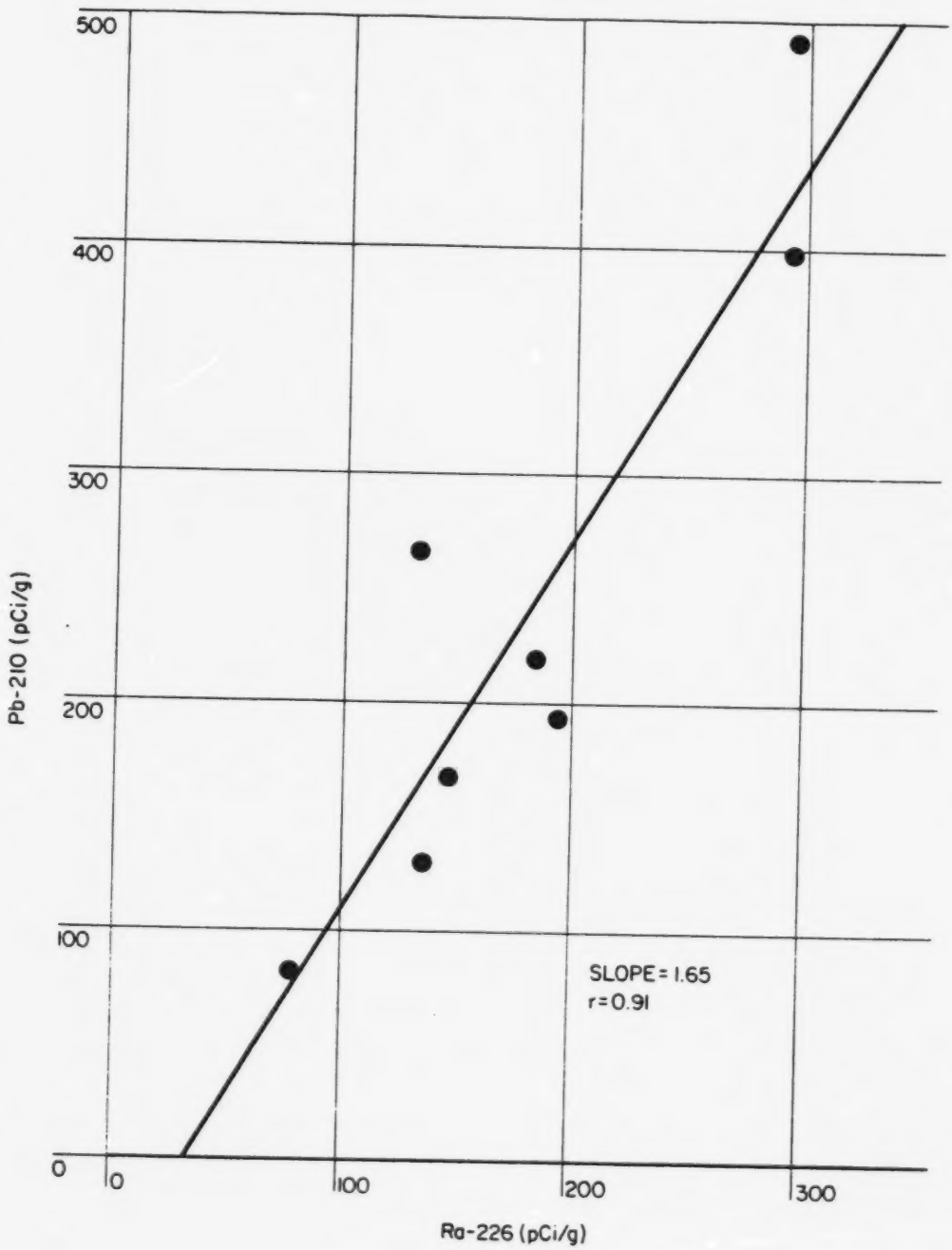


FIGURE 2.19: RELATIONSHIP BETWEEN Pb-210 AND Ra-226 CONTENTS OF WEATHERED TAILINGS SOLIDS FROM THE NORDIC MAIN TAILINGS MANAGEMENT AREA, ELLIOT LAKE (DATA FROM SMYTH, 1981)



enrichment of U and Th in the slime-enriched fraction (see Table 2.9). However, data from Smyth (1981) for shallow-depth weathered samples from the Nordic tailings suggest that a correlation with grain size does not exist for U and Th (Figure 2.20).

Data that could be extracted from the study by Dave et al. (1981) on the Nordic Main tailings reveal a similar lack of trends for various Th isotopes and U with grain size (Table 2.10). Although some differences are observed between the coarser and finer-grain-size fractions, they are not statistically significant. The data do suggest, however, that the coarse and fine grain sizes have different variances with respect to radionuclide concentrations, with the finer fraction exhibiting less variation.

2.5.3 Metals

Direct evidence for the segregation of metals by grain size is not readily available, but some indirect evidence exists. For example, it is known that most metals that occur in Elliot Lake tailings are present in the pyrite and other associated minor sulphides. Because most of the pyrite remains intact during the mill leach process, while other sulphides generally dissolve, the metals in the tailings probably occur in both the residual pyrite, as well as in the precipitated oxides or as coprecipitates with ferric hydroxides. In this way, the metals associated with the pyrite would be largely unsegregated and would occur at similar concentrations in both coarse- and fine-grained size fractions, while the metals associated with the precipitated solids would be concentrated in the fine-grained fraction.

Feenstra et al. (1981) found that the "leachable" iron contents of Williams Lake and Stanrock tailings were in the range of 0.1 to 1.0 percent by weight. This measurement supposedly represents the quantity of precipitated iron oxides. Nicholson (1984) reported metal concentrations associated with pyrite that was extracted from fresh Quirke Lake tailings (Table 2.11). Dubrovsky (1985) concluded that the ratios of metals (Cw, Pb, Zn, etc.) to iron dissolved in the pore water of the Nordic Main tailings reflected the ratios of metals to iron in the original pyrite. It may be possible, therefore, to estimate the total amount of metals associated with the precipitates by using the same Fe:metal ratios for the "leachable" iron concentrations reported by Feenstra et al. (1981). This approach would suggest that the concentrations of metals such as Co and Pb would be on the order of about 6 and 10 ppm respectively, in the fine grain fraction of the tailings

TABLE 2.9: PARTIAL COMPOSITION OF FINES AND SANDS IN ELLIOT LAKE TAILINGS

Constituent	Fines	Sands
*Total S (%)	1.73	0.10
Sulphate S (%)	1.67	0.09
Sulphide S (%) (by difference)	0.06	0.01
Th (ug/g)	70	30
U (ug/g)	30	10
Ra (pCi/g)	548	175
**U (ug/g)	19.1	15.8
Th (ug/g)	6.4	4.1
Ra-226 (pCi/g)	314	166
Pb-210 (pCi/g)	130	36
Po-210 (pCi/g)	77.4	17.8

* From Kaiman (1977).

** From Moffett and Tellier (1978).

FIGURE 2.20: PLOT OF U AND Th CONTENTS WITH MEAN GRAIN SIZE FOR WEATHERED TAILINGS SOLIDS FROM THE NORDIC MAIN TAILINGS MANAGEMENT AREA, ELLIOT LAKE (DATA FROM SMYTH, 1981)

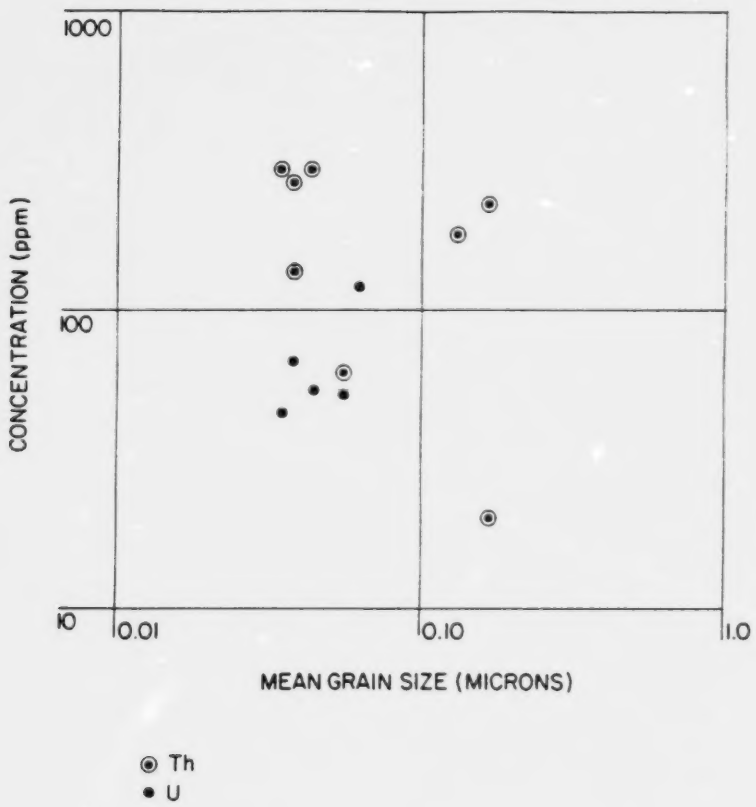


TABLE 2.10: RADIONUCLIDE CONCENTRATIONS IN GRAIN SIZE FRACTIONS FROM THE NORDIC MAIN TAILINGS (Data from Dave et al., 1981)

	-200+325 Fraction			-325 Fraction		
	Mean	Standard Deviation	No. of Samples	Mean	Standard Deviation	No. of Samples
Th-232 (pCi/g)	38.8	67.7	7	14.8	9.9	6
Th-228 (pCi/g)	58.9	45.2	7	45.0	18.4	6
Th-230 (pCi/g)	364	468	7	233	96.5	6
Ra-226 (pCi/g)	293	133	7	271	58.4	6
Pb-210 (pCi/g)	430	327	7	480	134	6
U (ppm)	47.3	36.7	6	52.2	34.6	6
Th (ppm)	145	189	6	169	110	6

TABLE 2.11: CONCENTRATIONS OF SELECTED ELEMENTS IN PYRITE FROM FRESH QUIRKE LAKE TAILINGS (from Nicholson, 1984)

Species	Tailings Pyrite (ppm)
Al	424
Ba	8
Ca	127
Co	613
Cu	576
Fe (%)	56
Mg	40
Mn	13
Ni	275
Pb	965
Si	173
Sr	6
Th	120
Ti	82
V	11
Zn	82
Zr	19

that contain the precipitates. This does not represent a large source of metals in the tailings compared to that associated with the residual pyrite.

The metal contents of high-grade Saskatchewan ores can be considerably higher than those associated with Elliot Lake ores. Segregation can also be quite pronounced because much of the metal content enters the solution phase during the milling process. The results of bench-scale testing reported by Sherritt (1980) suggest that up to 80% of Ni, 45% of Fe, 30% of Co, 60% of Cu, 40% of Mo, 30% of V and 80% of the available Zn are dissolved in the mill leaching solution (Table 2.12). Most of this mass is then reprecipitated during final neutralization, hence concentrations in the discharged tailings water are quite low (Table 2.13). Concentration of metal precipitates in the fine-grained fraction would be expected to parallel that of gypsum segregation in Elliot Lake tailings. Based on this assumption, it is possible that 50% to 70% of the available metals could occur in the fines. The actual amounts of metals in precipitated form could be higher than suggested by the amounts dissolved.

2.5.4 Pore Water Chemistry

The geochemical characteristics of the pore water associated with uranium mill tailings depends on the dissolution and precipitation reactions that occur for various mineral phases. Reactions with some solids such as gypsum, calcite and ferric hydroxides are governed by thermodynamic equilibrium while dissolution of solids such as feldspars, sulphides (i.e., pyrite), quartz and mica is regulated by kinetic controls (BEAK, 1985a). Because the tailings are presently discharged with process water that has pH values on the order of 8 to 11, the chemistry of the original pore water is characterized by low concentrations of most metals and moderate to high concentrations of sulphate (Table 2.14). Similarly, the pore water chemistry of freshly discharged tailings from high-grade Saskatchewan ores is expected to have low to moderate concentrations of most constituents with sulphate being the dominant dissolved solid (see Table 2.13). Originally, it is expected that the chemistry of pore water associated with a slime-enriched fraction would not be noticably different from that associated with coarser grained tailings. Some differences, however, will occur with time due to the influence of pyrite or other sulphide- and/or arsenide-mineral oxidation. This effect is quite noticeable in Elliot Lake tailings areas.

TABLE 2.12: EXTRACTION OF ORE COMPONENTS IN ACID LEACHING: TYPICAL GAERTNER AND DEILMANN ORE BLENDS (from Sherritt, 1980)

Component	Gaertner Ore			Deilmann Ore		
	Ore Analysis (%)	Solution (g/L)	Extraction (%)	Ore Analysis (%)	Solution (g/L)	Extraction (%)
U_3O_8	2.0	5.0	99.0	2.86	5.0	99.0
As	1.5	2.3-3.0	60-80	1.13	1.3-1.5	65-75
Ni	2.5	3.4-4.1	55-65	1.05	1.1-1.3	60-70
S	1.0		50*	0.77		*
Fe	3.5	3.1-3.9	35-45	3.04	1.9-2.1	35-40
Ca	0.35	0.5-0.6	57-69**	0.37		
CO_2	1.0	-	100	0.82	-	100
Al	9.0	1.0-2.0	4.4-8.8	10.3	1.1-1.8	6-10
Mg	3.0	0.8-1.8	11-24	2.9	0.9-1.3	17-25
SiO_2	50	0.2-0.6	0.2-0.5	50	0.7	0.8
Na	0.7	0.03	1.7	0.9	0.054	3.4
K	0.6	0.04	2.7	1.5	0.10	3.8
Co	0.076	0.050	26	0.081	0.055	39
Cu	0.029	0.023-0.046	32-63	0.087	0.044	29
Mo	0.006	0.0060	40	0.028	0.024-0.030	49-61
P_2O_5	0.16	0.17-0.20	43-50	0.15		
Ti	0.40	0.003-0.013	0.3-1.3	0.62	0.0083	0.8
V	0.08	0.040-0.058	20-29	0.092	0.035	22
Zn	0.08	0.078-0.163	39-82	0.033	0.022	38
Cl	0.05	0.020	16			
F	0.05	0.020-0.035	16-28			

* Sulphur extractions difficult to estimate because of high $S(SO_4)$ in leach residues.

** Net Ca extraction in two stage leach will be 0 because solutions are gypsum saturated.

N.B. The leach solution analyses correspond to feeds to uranium recovery; full strength leach liquors are 4 to 5 times more concentrated (except for Ca).

TABLE 2.13: SUMMARY OF QUALITY OF KEY LAKE PROCESS WASTE WATERS PRODUCED BY BULK PRECIPITATION AND FINAL NEUTRALIZATION ROUTES (from Sherritt, 1980)

		Testwork Wastewater Quality (mg/L)	
		Bulk Precipitation Route	Final Neutralization Route
		Range of Testwork Values	Range of Testwork Values
Arsenic	As	0.4-2.4	0.01-0.3
Copper	Cu	0.01-0.04	0.1
Lead	Pb	0.01-0.8	0.01-0.9
Nickel	Ni	0.02-1.1	0.1-0.6
Zinc	Zn	0.01- 0.1	0.1
Aluminum	Al	0.2-2.4	0.1-2.3
Cadmium	Cd	0.01	0.1
Calcium	Ca	605-777	482-693
Chloride	Cl	19-26	21-49
Chromium	Cr	0.01-0.06	0.1
Cobalt	Co	0.01-0.06	0.1
Fluoride	F	1-4	1-5
Iron	Fe	0.01-0.4	0.1-1.5
Magnesium	Mg	0.1-0.9	0.1-3.3
Manganese	Mn	0.01- 0.1	0.1
Mercury	Hg	0.005	0.005
Molybdenum	Mo	0.2-1.3	0.1-1.3
Phosphorus	P	0.01-0.5	0.1-1.7
Potassium	K	20-105	46-63
Selenium	Se	0.01-0.5	
Silicon	Si	0.6-11	0.4-5.9
Sodium	Na	48-78	61-80
Sulphur	S	520-570	510-550
Titanium	Ti	0.006-0.02	0.1
Uranium	U	0.2-1.7	0.1-0.5
Vanadium	V	0.06-0.26	0.1
Radium	Ra-226 (pCi/L)	452-635	150-500

Neutralization to pH 11-11.5 with lime.

TABLE 2.14: CONCENTRATIONS OF SELECTED SPECIES IN THE DISCHARGE WATER FROM FRESH QUIRKE LAKE TAILINGS
(from Dubrovsky et al., 1985a)

	Quirke Tailings
pH	10.9
Fe Total	1.4
Al	3.0
Ca	612
Mg	0.35
Na	36
K	142
SO_4	1,325
Cl	14
Cu	0.06
Zn	0.04
Ni	0.09
Co	0.09
Pb	0.17
Mn	0.04
Ra Total (pCi/L)	1,679
NO_3	575

Deposition of tailings to impoundments by slurry discharge has resulted in areal grain-size segregation of many deposits. An ideal representation of the grain size distribution is given in Figure 2.21, which shows the sand or coarse-grained fraction in proximity to the discharge pipe on the "beach" and the location of the fine-grained fraction or slimes at the far extent of the tailings pond. Because of these trends, the study of presently existing tailings impoundments can provide information with regard to expected behaviour of coarse- and fine-grained tailings.

Noticeable differences in chemistry and other characteristics were observed in one study of shallow pore water and tailings solid samples collected from above the water table on the Nordic Main tailings (Smyth, 1981). A number of sites was studied, two of which represent the contrasting coarse-grained (T5) and fine-grained (T3) areas respectively. The mean grain size distribution with depth is shown for both of these sites in Figure 2.22. The pore water at the coarse-grained site (T5) is characterized by lower pH and higher specific conductance values than the pore water at the fine-grained locale (T3) (Figure 2.23). In addition, the concentrations of many chemical constituents are higher in pore water at the coarse-grained site (Figures 2.24a and 2.24b). The reasons for these observations become apparent when pyrite oxidation is considered.

It is known that the oxidative dissolution of pyrite in Elliot Lake tailings produces sulphuric acid that results in pore water with low pH and elevated concentrations of many metals, sulphate and some radionuclides (Cherry et al., 1981; Dubrovsky et al., 1985a; Dubrovsky et al., 1985b). However, it is highly probable that the rate and extent of pyrite oxidation is controlled by transport of oxygen into the tailings that is, in turn, controlled by the effective diffusivity of the porous tailings (Nicholson, 1984; IEC BEAK, 1985a). Because diffusion of oxygen through water is about 4 orders of magnitude less than diffusion through air, water-filled pores provide an effective barrier to oxygen transport in the tailings.

An estimate of the effective diffusion coefficient for oxygen through a porous medium can be made if the volumetric water content and porosity are known (Currie, 1970). The estimated effective diffusion coefficients for oxygen at the two sites vary by about 3 orders of magnitude with the lower value associated with the fine-grained site (Smyth, 1981).

FIGURE 2.21: A SCHEMATIC CROSS-SECTION THROUGH A TAILINGS DEPOSIT SHOWING THE GRAIN SIZE DISTRIBUTION WITH DISTANCE FROM THE DISCHARGE PIPE (MOFFETT, 1976)

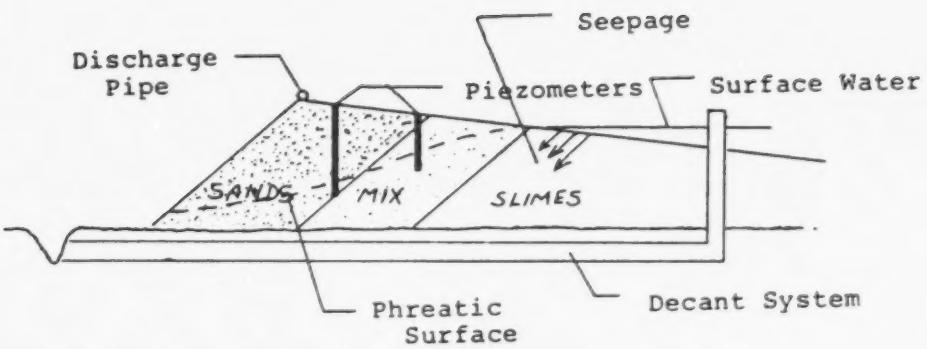


FIGURE 2.22: VARIATION OF MEAN GRAIN SIZE WITH DEPTH FOR THE FINE-GRAINED (T3) AND COARSE-GRAINED (T5) SITE ON THE NORDIC MAIN TAILINGS MANAGEMENT AREA, ELLIOT LAKE (SMYTH, 1981)

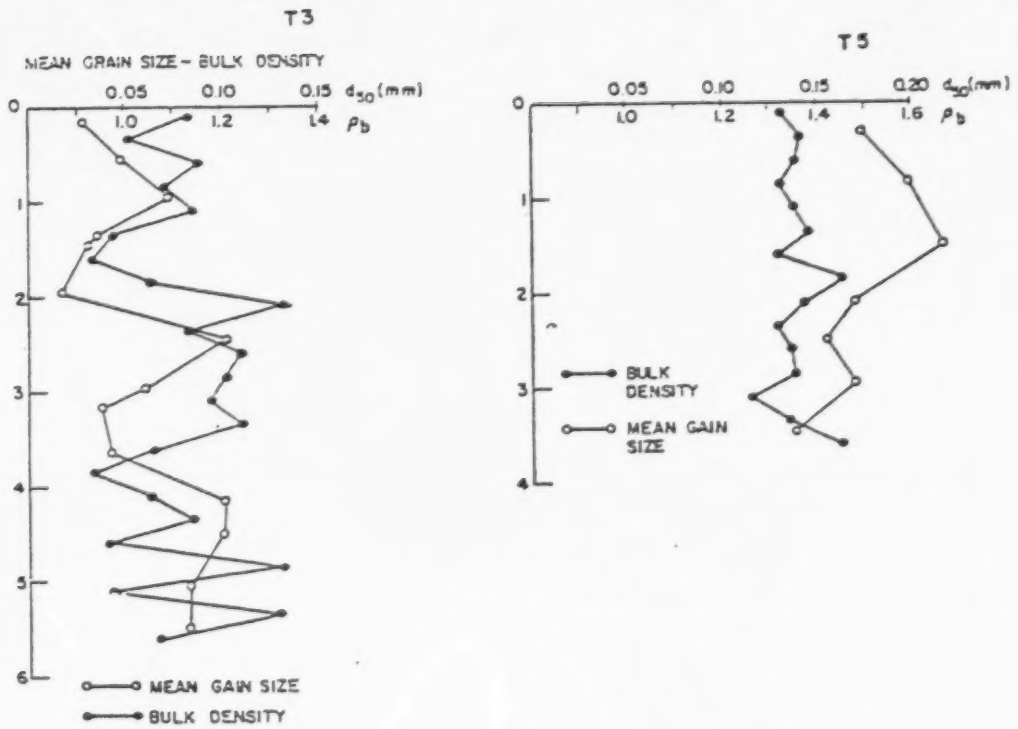


FIGURE 2.23: SPECIFIC CONDUCTANCE OF pH VALUES OF PORE WATER SAMPLES COLLECTED ABOVE THE WATER TABLE IN FINE-GRAINED (T3) AND COARSE-GRAINED (T5) TAILINGS FROM THE NORDIC MAIN TAILINGS MANAGEMENT AREA, ELLIOT LAKE (SMYTH, 1981)

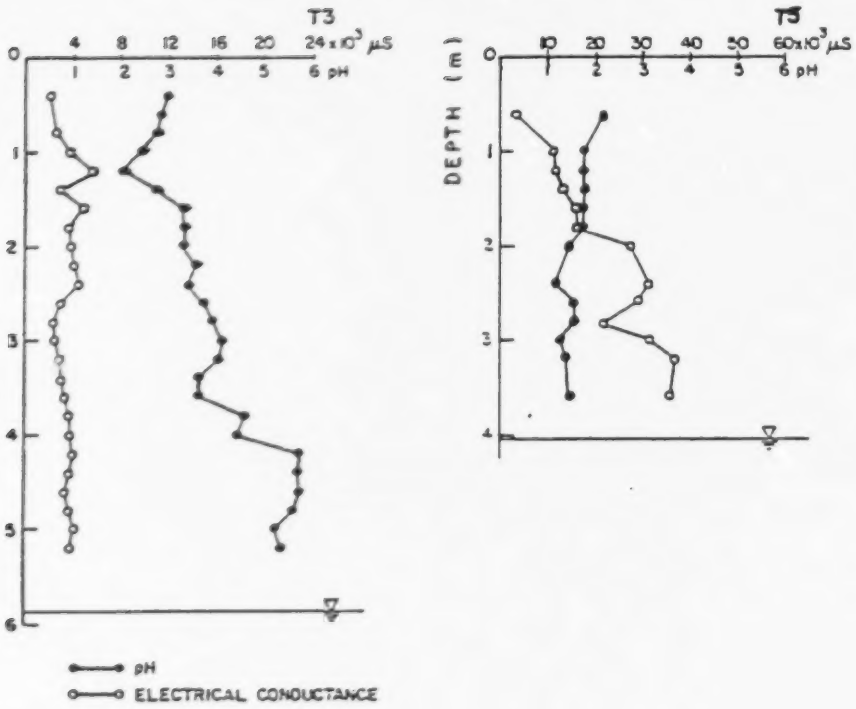


FIGURE 2.24a: CONCENTRATIONS OF SELECTED ELEMENTS IN PORE WATER SAMPLES FROM A FINE-GRAINED TAILINGS ON THE NORDIC MAIN TAILINGS (FROM SMYTH, 1981)

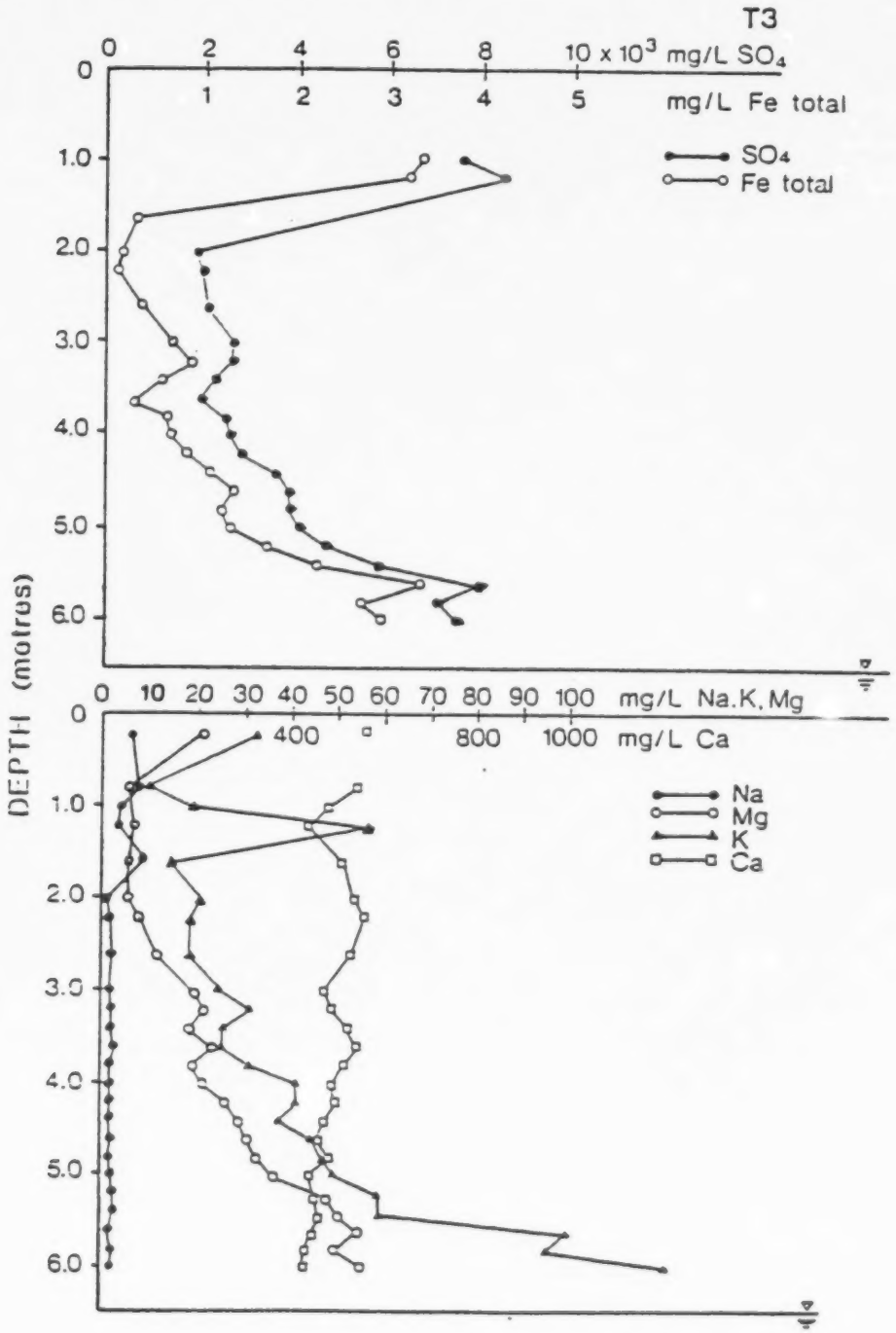
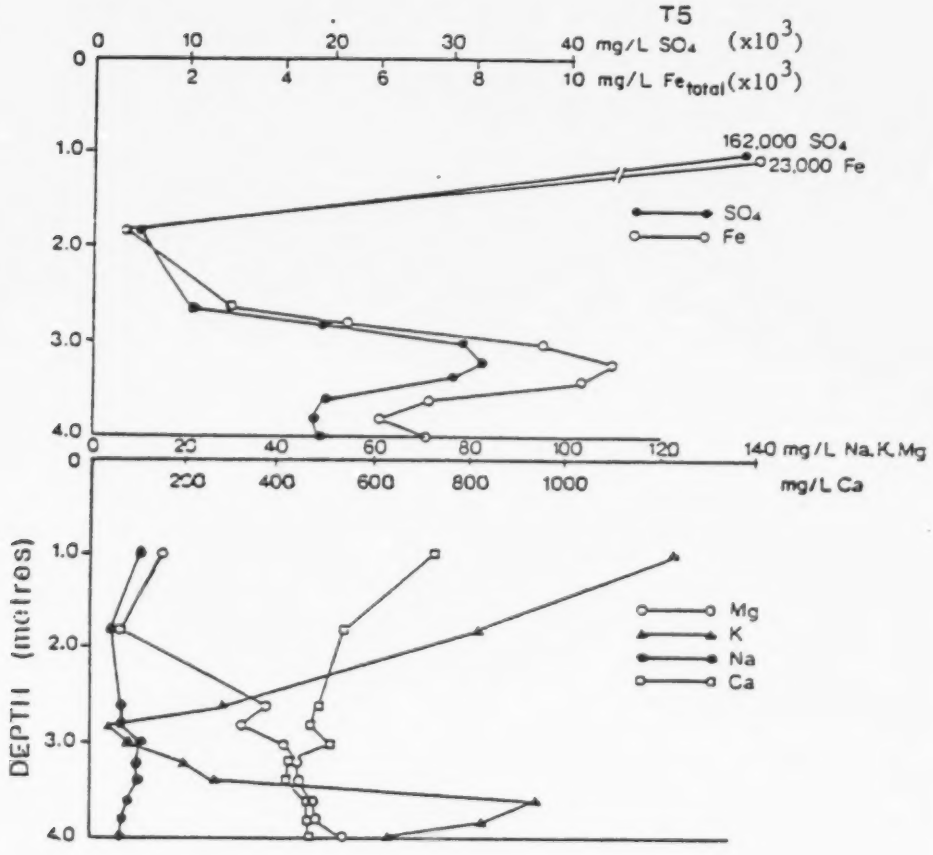


FIGURE 2.24b: CONCENTRATIONS OF SELECTED ELEMENTS IN PORE WATER FROM A COARSE-GRAINED TAILINGS FROM THE NORDIC MAIN SITE (FROM SMYTH, 1981)



It is known that fine-grained porous media retain greater percentages of water than coarser-grained material under drainage (negative pressure) conditions. It follows, therefore, that rates of pyrite oxidation will be smaller in the fine-grained fraction of tailings. The resulting restriction of oxygen transport in the fine material is exhibited by less penetration of oxygen in the gas phase with depth (Figure 2.25). In the case of site T3, the very high O_2 levels at shallow depths have likely resulted from movement in dessication cracks that occurred at the surface during drying of this silty material. In any case, above-background levels of O_2 were observed at the 2 m depth in the coarse-grained area (T5) as opposed to only the 1 m depth in the fine-grained area (T3). The lower pH and high concentrations of many consitutents in the pore water at the former site are consistent with the higher expected rates of oxidation there.

The effect of the rapid oxidation expected at the site containing the coarse-grained fraction can also be seen in terms of the relative depletion of pyrite. Data reported by Moffet et al. (1977) show the effect of different oxidation rates and their effect on the quantity of residual pyrite with depth in coarse- and fine-grained tailings (Figure 2.26). In this case, the tailings that had been weathering for about 20 years, reveal a more pronounced depletion of pyrite in the "sands" or coarse-grained tailings. Another study indicated differences in pore water chemistry located in sands and slimes (Moffett and Tellier, 1978). The quality of the pore water collected from the west area at the Nordic tailings site reflects the grain-size characteristics of the sample location with lower concentrations of most constituents within the fine-grained material (Table 2.15).

It should be noted that the correlations observed here of less degradation in water quality associated with slime-rich tailings is not due to a lower "reactivity" of the fines but is actually a result of water retention. Lower pyrite oxidation rates are a direct result of higher moisture contents in fine-grained tailings. This suggests that sand-enriched zones with a water-table near the ground surface may result in similar behaviour of reduced oxidation rates and subsequent increases in pore water quality. To some extent higher pH values within the slime enriched area may also be due to the slightly greater abundance of residual carbonate in that fraction.

In the absence of sulphide-mineral oxidation, it is expected that very few differences would occur between coarse- and fine-grained fractions of the weathered tailings. Although studies are now being conducted to characterize the mineralogy and

FIGURE 2.25: CONCENTRATION PROFILES FOR OXYGEN NITROGEN AND CARBON DIOXIDE IN THE GAS-FILLED PORES IN THE FINE-GRAINED (T3) AND COARSE-GRAINED (T5) TAILINGS ON THE NORDIC MAIN TAILINGS MANAGEMENT AREAS, ELLIOT LAKE (SMYTH, 1981)

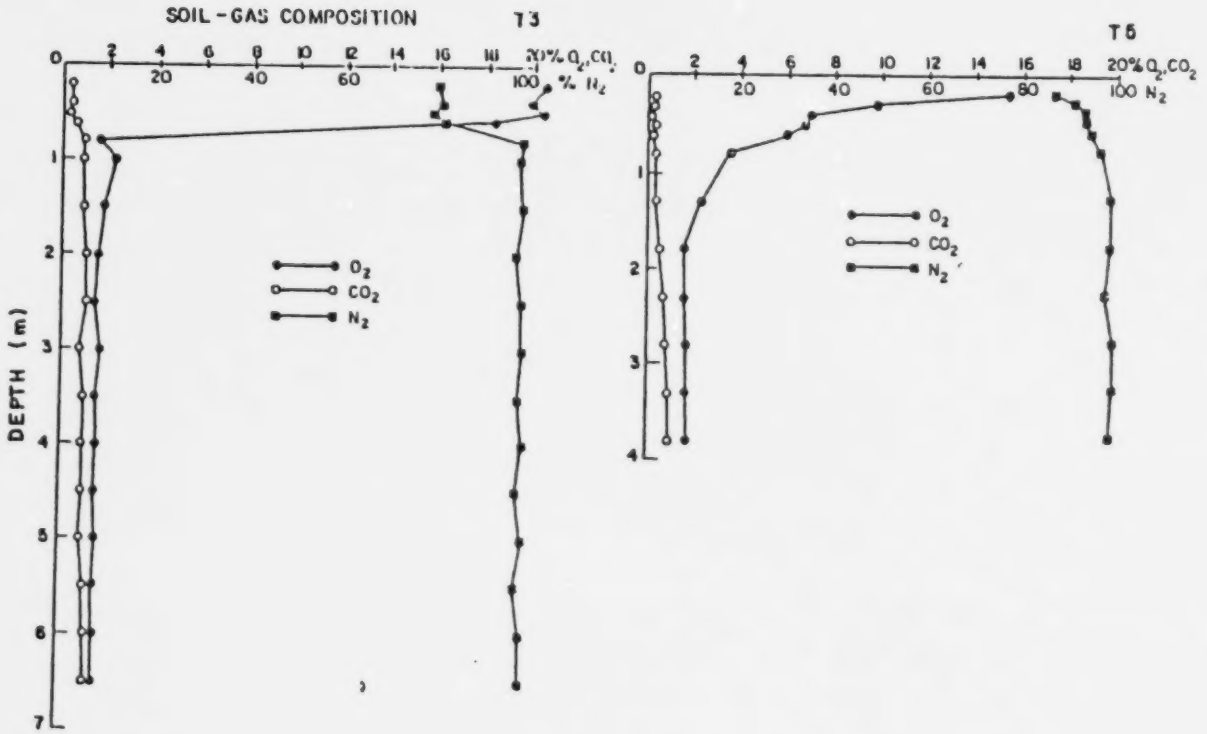


FIGURE 2.26: PYRITE CONTENT PROFILE OF 20-YEAR-OLD TAILINGS FROM ELLIOT LAKE (MOFFETT et al., 1977)

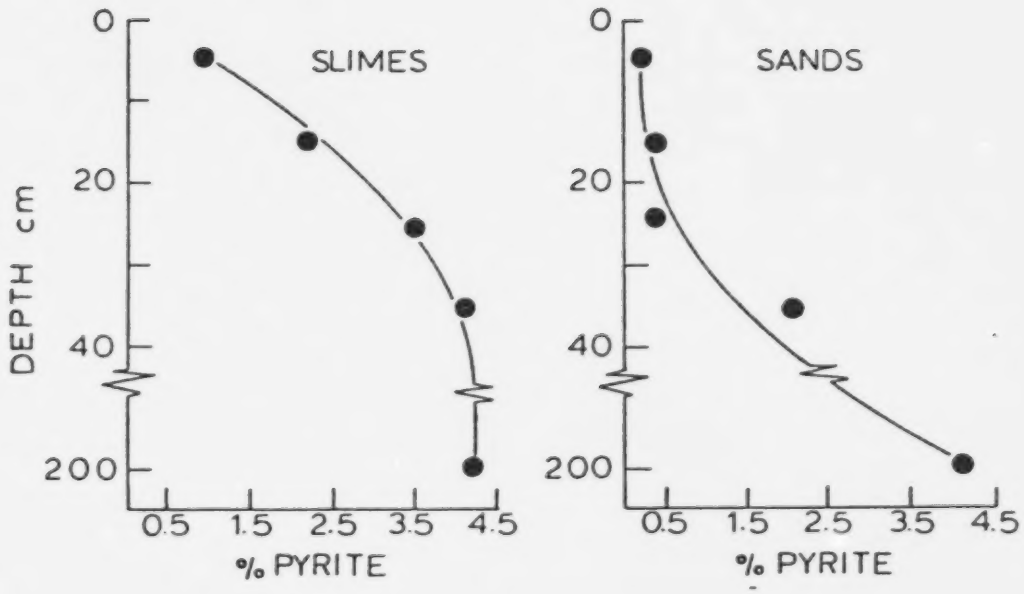


TABLE 2.15: WATER QUALITY IN THE TAILINGS BASIN (from Moffett et al., 1977)

Sample Location	mg/L			pCi/L					ug/L
	Acidity	TDS*	Fe	Ra-226	Pb-210	Th-232	Th-230	Th-228	U
Beneath Sands	12,120	24,200	1,744	27	4,067	1,400	16,000	500	5,200
Beneath Slimes	L 50	4,840	68	137	42	-	-	L 15	198
Seepage	1,790	4,570	604	13	32	80	800	150	370

* Total Dissolved Solids

radiochemistry of the Saskatchewan tailings, data are not yet available (G. Feasby, pers. comm., 1985). It is important to know whether primary arsenide or sulphide minerals remain in the neutralized tailings. If the quantity of sulphides or arsenides is insufficient to cause acidification, the pore water chemistry would likely remain similar in nature to the freshly discharged effluent.

2.6 Environmental Effects

The major environmental considerations associated with uranium tailings relate to releases of radionuclides and other trace contaminants to the environment via water and air transport, and subsequent uptake by biota and humans. As shown in Figure 2.27, major aquatic pathways for contaminants include water, vegetation and animal. In addition, release and transport of radon gas and transport of radionuclides by wind erosion (dust) will occur (Figure 2.28).

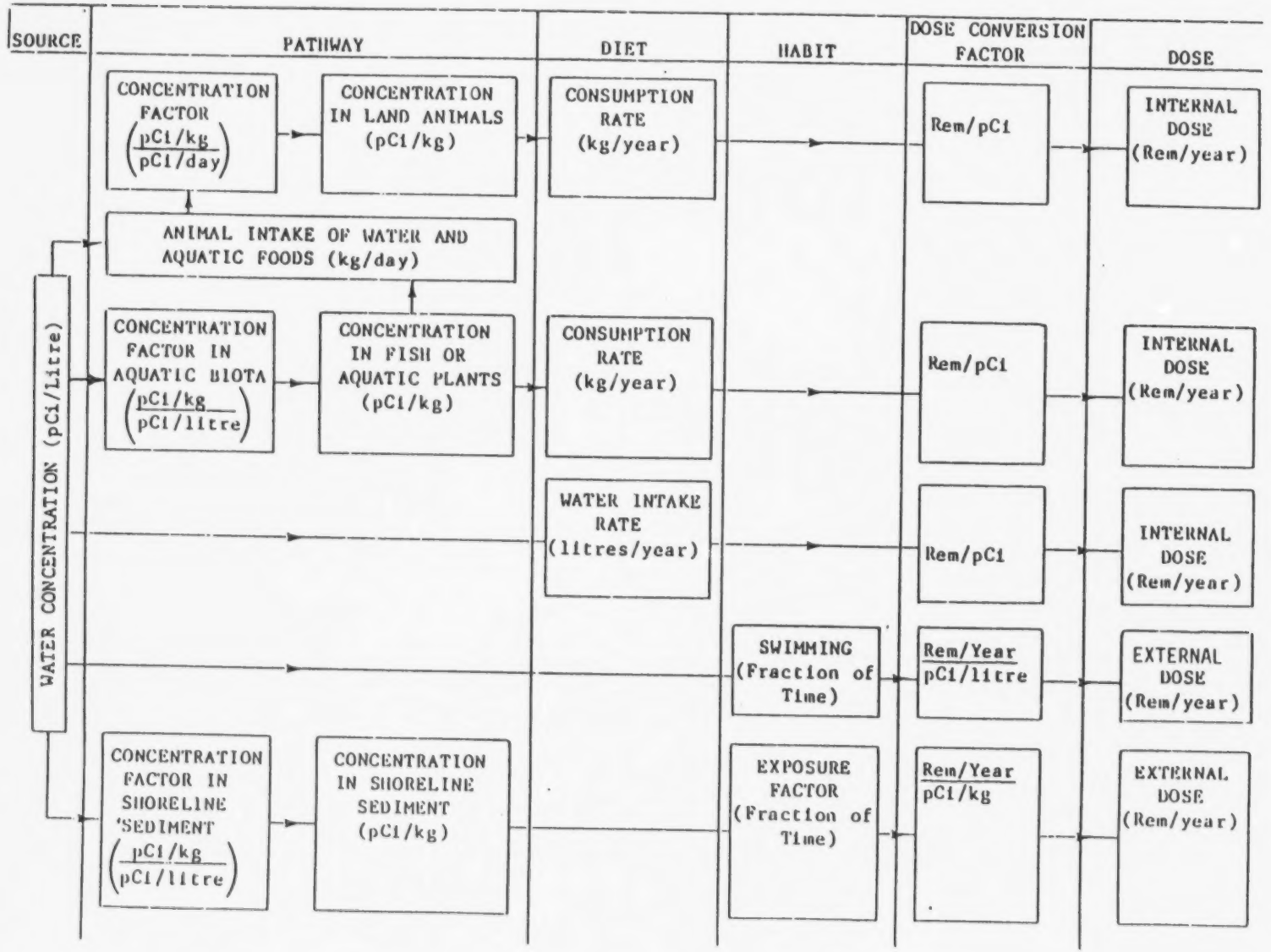
With the exception of a small number of preliminary revegetation trials, there have, to date, been no site-specific studies of environmental impacts of slime-enriched tailings. Indeed, given that most existing tailings impoundments are comprised of areas of both coarse and fine particles, the individual contribution of the slimes to environmental pathways is difficult to assess. Nonetheless, based on characterizations of geotechnical and geochemical properties presented in the previous sections, potential environmental impacts of slime-enriched tailings can be addressed in a preliminary fashion.

2.6.1 Releases to Aquatic Ecosystems

The transport of contaminants from a tailings impoundment can occur by a number of processes, the most significant of which will usually be the movement of dissolved constituents in the subsurface pore water. Estimation of contaminant fluxes through pore water movement requires knowledge of hydrogeological processes that control subsurface flow in a tailings impoundment.

The relative concentrations of some radionuclides and metals as well as some secondary minerals will be greater in the slime fraction of tailings. Therefore, there will be proportionally more mass of such contaminants per mass of total tailings available to enter the environment. However, the critical parameter is not necessarily the total

FIGURE 2.27: EXPOSURE PATHWAYS AND INDIVIDUAL DOSE CALCULATIONS FOR RADIONUCLIDE RELEASES TO SURFACE WATER (IEC BEAK, 1983)



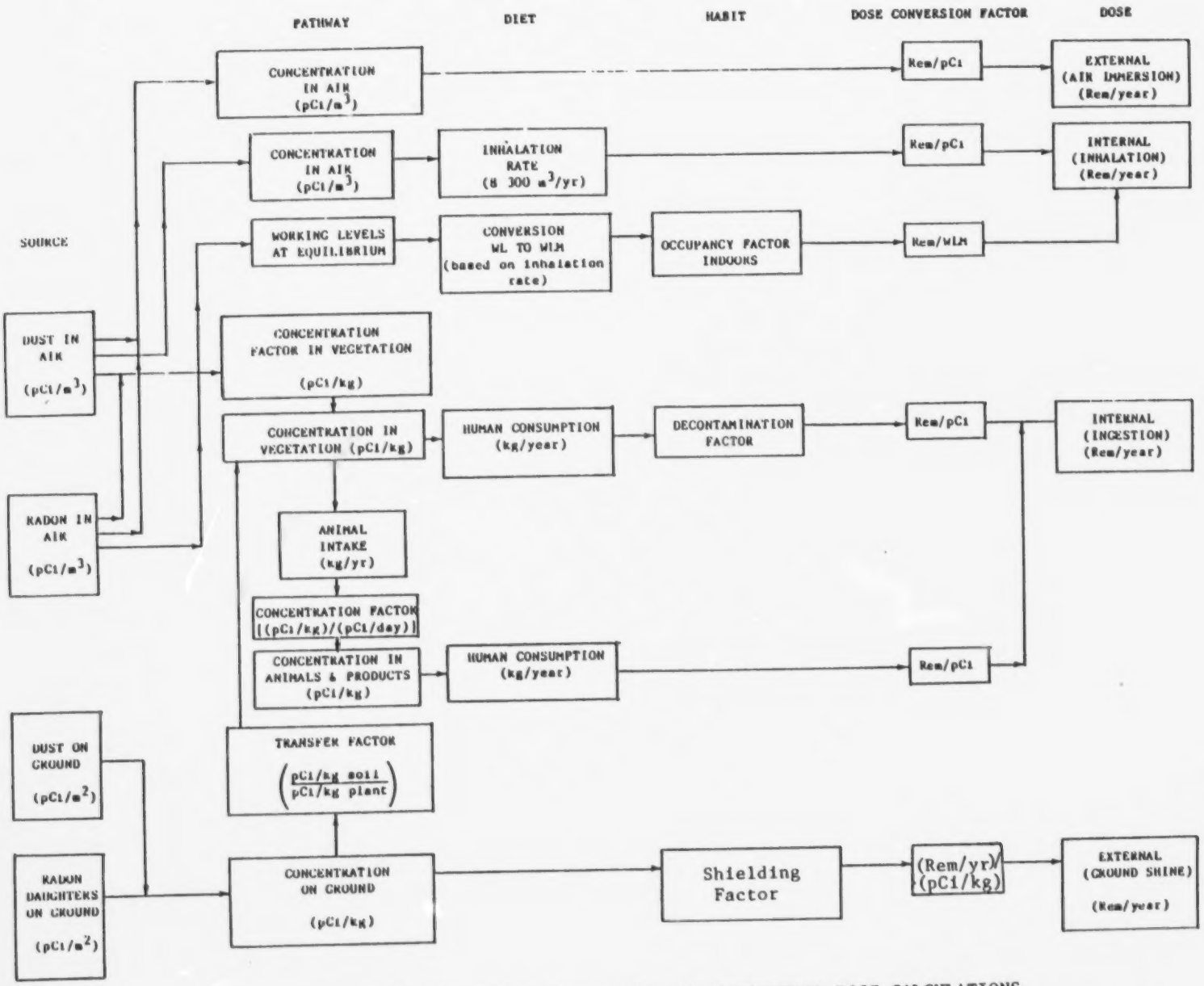


FIGURE 2.28: EXPOSURE PATHWAYS AND INDIVIDUAL DOSE CALCULATIONS FOR RADIONUCLIDE RELEASES TO THE ATMOSPHERE (IEC BEAK, 1983)

available mass but the rate or flux at which such contaminants exit from the tailings impoundment. The concentrations of many tailings constituents in the pore water of tailings in coarse-grained and fine-grained zones at shallow and deep sites are given in Table 2.16. It is observed that most species occur in lower concentrations in the finer-grained material than in the coarser-grained material. Therefore, even if the mass flux of water through the tailings were the same for both coarse- and fine-grained fractions, the flux of many contaminants from tailings containing a large portion of slimes would be less than the flux exiting a sand-enriched deposit.

It should be noted that at present, the 20 to 30 year old inactive tailings deposits at Elliot Lake do not contain low-pH water throughout. To date, varying degrees of acidification have occurred in addition to some neutralization of low-pH pore waters that have moved through the tailings. The presence of some residual carbonate solids ($CaCO_3$) and aluminum hydroxides provides some capacity for neutralization of the acidic pore water that migrates through the deeper tailings (Dubrovsky et al., 1985a). However, the quantity of pyrite present in the tailings (at Elliot Lake at least) provides a much greater potential for acidification than the existing potential for neutralization. If the conditions continue as in the past, it is inevitable that low-pH pore water will eventually exit the tailings mass. This has already been observed in one location in proximity to the Nordic Main tailings where contaminated acidic pore water has migrated beyond the tailings impoundment in the underlying sandy deposit (Blair et al., 1981; Morin et al., 1982).

The major differences in expected behaviour between sand- and slime-enriched tailings are related to time for acidification of the tailings mass to occur and the flux of contaminants from the site. Slime-enriched tailings are likely to be characterized by longer periods for acidification both because of slower oxidation rates and the presence of higher concentrations of buffer materials such as carbonates and aluminum hydroxides. Therefore, it is expected that the flux of contaminants related to acidification will be lower for slime-enriched tailings.

An additional condition that must be considered when calculating release rates from slime-enriched tailings is that of consolidation. Because the fine-grained tailings are generally under-consolidated and because volume reduction will occur in time, some pore water will be displaced from the tailings pore spaces to migrate either as surface or

TABLE 2.16: CONCENTRATIONS OF ELEMENTS IN PORE WATER FOR COARSE- AND FINE-GRAINED TAILINGS AT TWO DEPTHS

	Quirke Tailings Discharge*	Sandy Tailings Depth 1 m**	Sandy Tailings Depth 9 m***	Silty Tailings Depth 1 m**	Silty Tailings Depth 9 m***
pH	10.9	1.4	5.8	2.4	5.9
Fe (total)	1.4	23,038	12,520	3,343	3,275
Al (ppm)	3.0	230	0.8	41.2	1.6
SiO_2 (ppm)	-	33.0	40.4	168	27
Ca (ppm)	612	734	400	484	396
Mg (ppm)	0.35	15.6	460	19	246
Na (ppm)	36	11.9	14	3.3	3.7
K (ppm)	142	123	170	30	135
SO_4 (ppm)	1,325	162,000	28,000	2,870	7,810
PO_4 (ppm)	-	L 2.0	-	L 2.0	-
Cl (ppm)	14	24	4.9	6.4	1.0
F (ppm)	-	-	L 2.0	L 2.0	3.4
Cu (ppm)	0.06	11.3	0.05	4.4	L 0.01
Zn (ppm)	0.04	15.9	7.3	2.1	1.0
Ni (ppm)	0.09	27.1	16	3.6	1.3
Co (ppm)	0.09	34.9	14	3.9	1.9
Pb (ppm)	0.17	-	0.67	-	0.51
Mn (ppm)	0.04	1.5	15	0.7	95
Alk (as HCO_3) (ppm)	-	-	232	-	165
Ra Total (pCi/L)	1,679	-	132	-	0.60
NO_3 (ppm)	575	-	-	-	-

* Analysis done by Rio Algom Laboratory, March 1977, A.J. Vivyurka, written communication (data from Dubrovsky et al., 1985a).

** Data from Smyth (1981).

*** Data from Cherry et al. (1982).

subsurface seepage. This volume of water would be in addition to the normal infiltration flux arising from rain and snow melt. The time dependent release of this pore water can be estimated from consolidation theory.

2.6.2 Atmospheric Releases

Potential atmospheric releases from the tailings surface include fugitive dust and radon gas exhalation.

Fugitive Dust

Fugitive dust represents a potentially significant radionuclide source in surface disposal areas. Losses are most severe from bare exposed tailings with low moisture contents. Particulate loss is dependent on the carrying capacity (i.e., velocity) and duration of wind and the grain size distribution of the surface tailings. Tailings affected by wind erosion generally undergo a gradual depletion of fines from the surface with an accompanying decrease in particulate loss over time. This is balanced, to some degree, by surface weathering reactions and physical breakup of particles due to frost and physical abrasion. Given the relatively small mean grain size of slime-enriched tailings, fugitive dust emissions from exposed, low-moisture slimes may be expected to be potentially higher than from unsegregated tailings, but this potential will depend upon the degree of surface roughness on the tailings and the presence of larger saltating particles which may "kick" the finer particles up into the air.

Wind erosion has historically been a problem on abandoned uranium tailings in the American mid-west, where climatic conditions produce an annual net moisture deficit. Certain areas of northern Saskatchewan where annual mean precipitation averages less than 35 cm, could experience similar problems. As noted in Section 2.4.2, the water content of surface slimes from Beaverlodge ranged from 9 to 62%. Field observations at the Gunnar-Main tailings indicate frequent summer dust storms and, during the winter months, snow discolouration by windblown tailings occurs. Since the Gunnar Main tailings are composed of unsegregated tailings of relatively coarse grain size, the net observed dust generation (20 years after abandonment) may be due, in large part, to generation of fines through weathering processes and the effect of saltating larger, sand-sized particles.

Wind tunnel experiments, conducted on fully dried fine uranium tailings from Key Lake, produced very low dust loss even at high wind velocities (Sherritt, 1980). This was attributed to cohesive properties of the slimes which resulted in a cemented layer upon drying. If these slimes were broken up through chipping by saltating sand, or possibly through freeze/thaw or biological activity, higher levels of dust generation may have resulted.

In the Elliot Lake region, climatic moisture excess (greater than 80 cm mean annual precipitation) significantly reduces the potential for loss of fines. Surface water contents of slimes, as measured at Dennison and Quirke Mines, remains close to saturation even during the summer months (see Table 1).

Radon Gas Release

Radon exhalation at the tailings surface represents another form of contaminant migration from the impoundment. Radon exhalation to the atmosphere is expected to occur from tailings derived from all types of uranium ores. Radon flux concentrations at the surface will be a function of the activities of radium (parent) present in the tailings and the flux of radon from the tailings (see Figure 2.29 as an example of calculated flux). Since radium is concentrated in the fine or slime fraction of tailings, one would expect potentially high levels of radon gas in areas containing a large fraction of fines. As a gas, radon will be transported through the porous tailings in a number of ways.

One mechanism responsible for radon movement would be diffusion. Because diffusion usually results in low fluxes, and because the half-life of radon is on the order of four days, only the radium that is decaying close to the surface is likely to contribute to radon exhalation through this process. In coarse-grained tailings, significant drainage of water is likely and diffusion of radon would occur mostly through the gas in the pore spaces. This would likely represent a relative maximum for the rates of radon movement by diffusion. Even then, however, fluxes would remain low, and only shallow surface zones in the tailings would affect radon exhalation. In finer-grained tailings, pore spaces would retain greater percentages of water which reduces the effective porosity and further restricts the diffusion of radon. This effect is shown in Figure 2.30. In fine tailings and/or wet zones, the effective depth from which radon is generated and exits the surface by diffusion is likely to be quite small. The depth of influence for radon

FIGURE 2.29: RADON FLUX CALCULATED AS A FUNCTION OF THE Ra CONCENTRATION IN TAILINGS (MACLAREN, 1984)

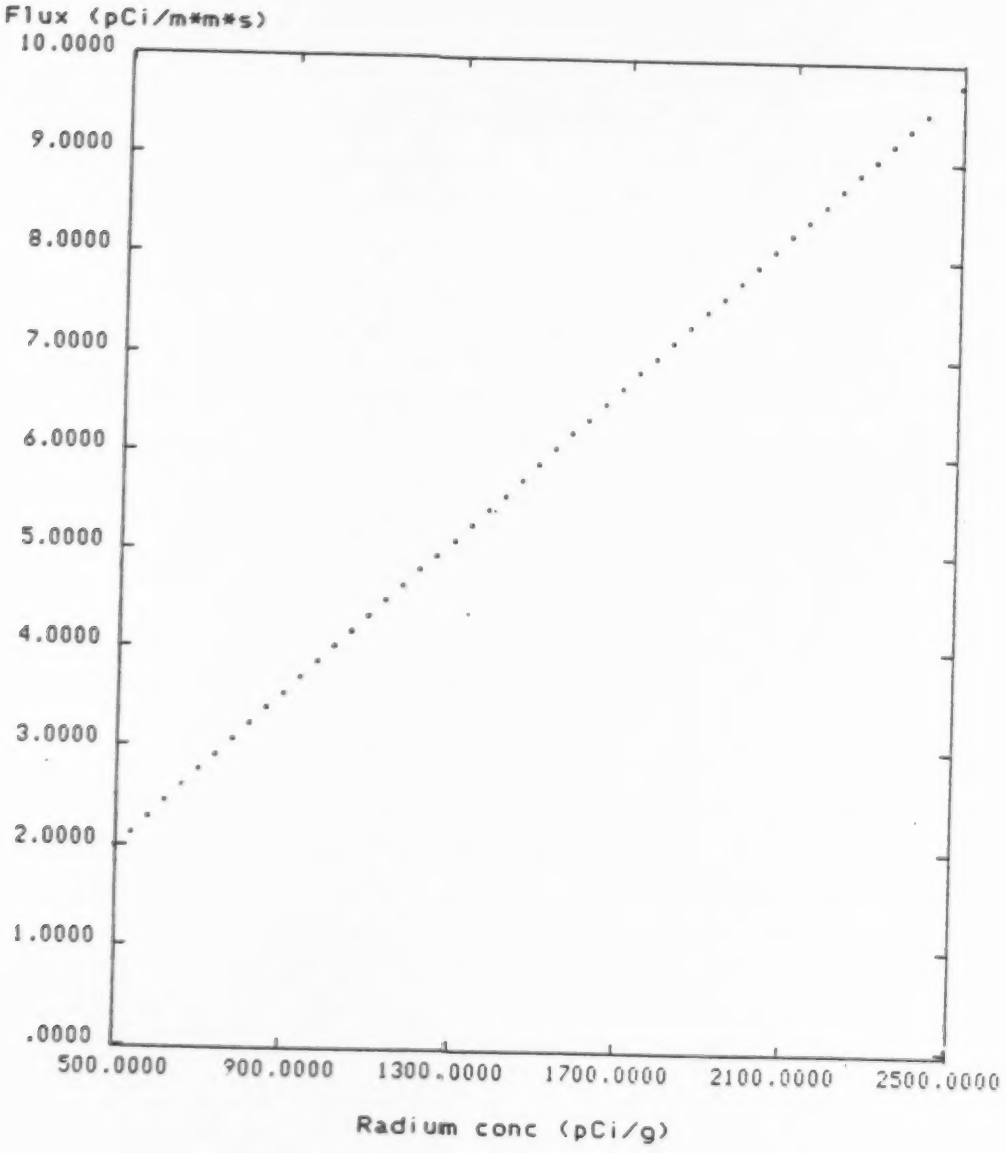
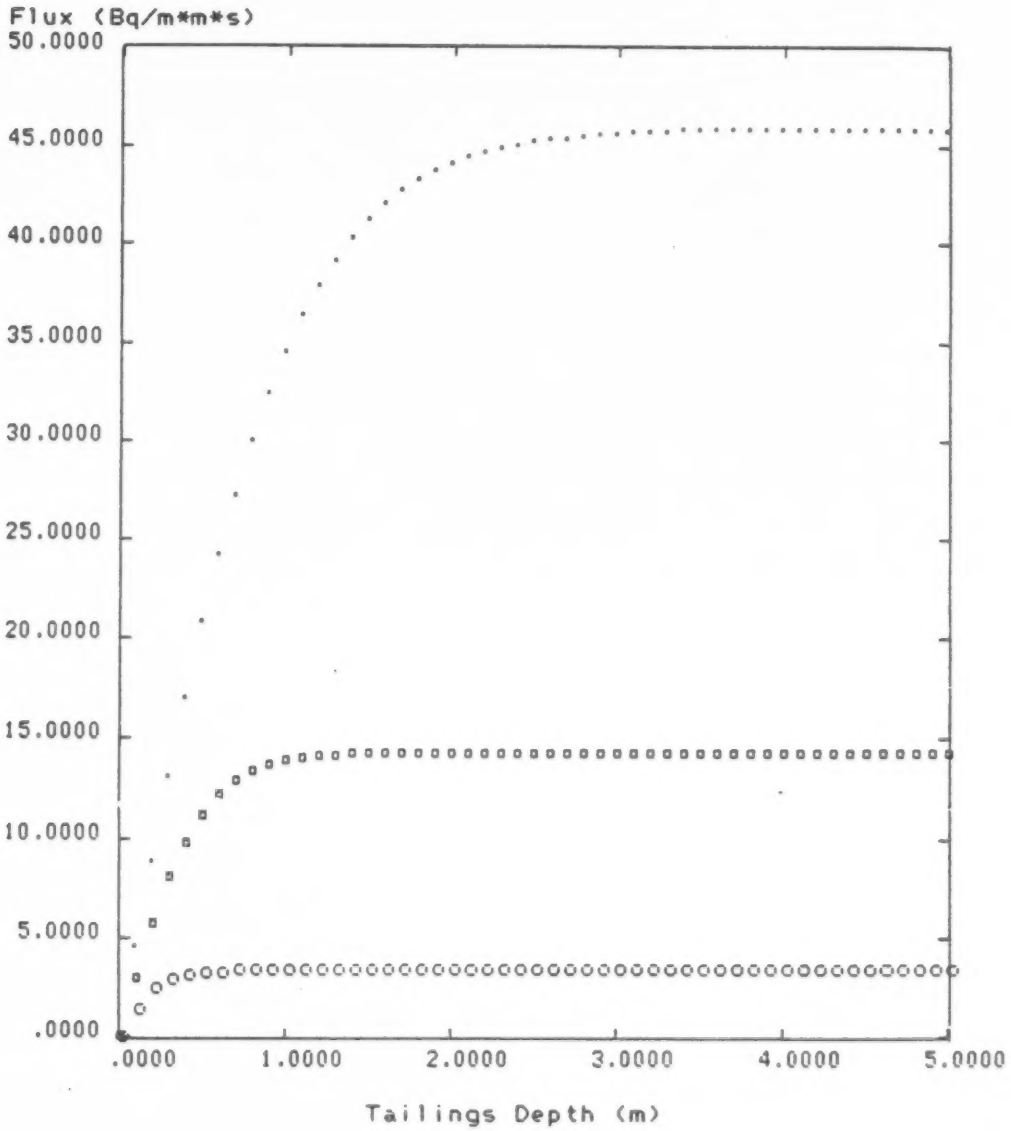


FIGURE 2.30: RADON FLUX AS A FUNCTION OF TAILINGS DEPTH WITH VARYING EFFECTIVE POROSITY. DRY TOTAL POROSITY IS 0.4 (MACLAREN, 1984)



Legend
. -- Effective Porosity - 0.3
□ -- Effective Porosity - 0.2
o -- Effective Porosity - 0.1

Radon flux as a function of tailings depth
with varying effective porosity.
Dry porosity is 0.4

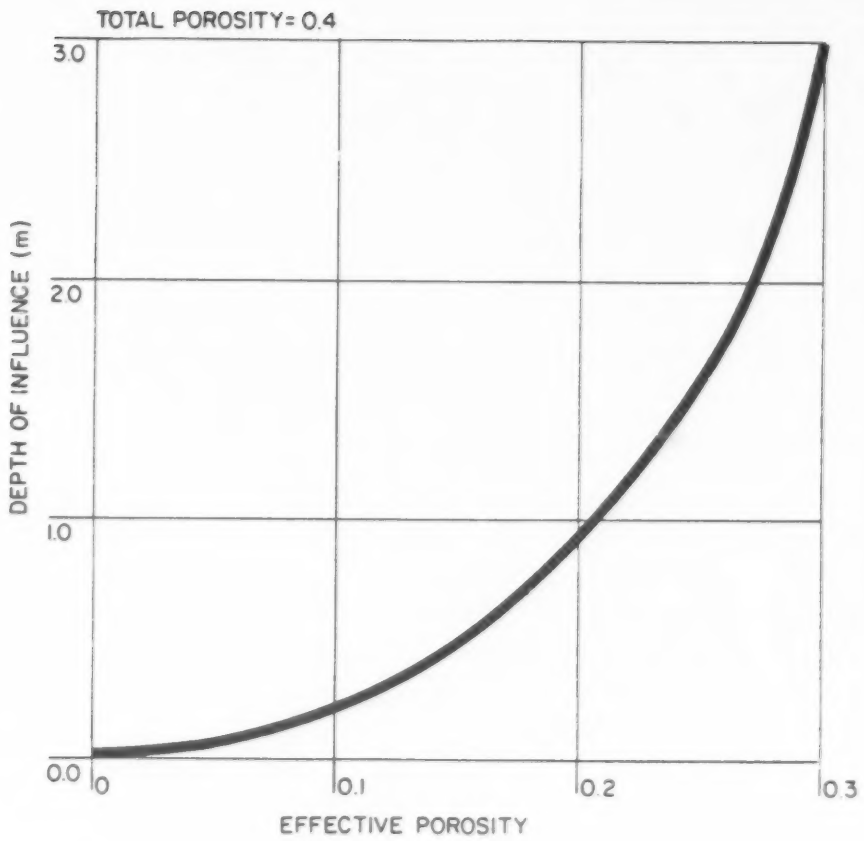
contribution with effective porosity is shown in Figure 2.31. In this way, diffusion of radon is similar to the diffusion of oxygen. The processes are reversed, however, in that oxygen migrates into the deposit where it is consumed by pyrite oxidation.

A second mode of radon transport in the porous tailings involves changes in barometric pressure. The gas in the pore spaces above the water table expands and contracts in response to atmospheric fluctuations. Upon increasing barometric pressure, atmospheric gas is compressed into the top zone of the tailings. During that time, radon would be continuously generated and released to the gas in the pores. When the barometric pressure decreases, the gas in the pores expands and the excess gas near the surface would exit to the atmosphere. This "barometric pumping" is a cyclic process that would likely be more effective in transporting radon in coarse-grained than in fine-grained tailings. The depth within the tailings affected by this pumping depends on the depth to the zone of complete pore saturation (i.e., either the water table or the top of the capillary fringe). Because this process obeys Boyle law, and because atmospheric fluctuations are rarely greater than 5%, the affected zone would be limited to about 5 cm for every metre that the saturated zone extends below ground surface.

A third mechanism of radon transport in the tailings involves the infiltration of moisture. When rainfall or snowmelt occurs, the water moves downward into the pore spaces that are partially filled with gas. The pore gas existing in a particular zone will be displaced by the water as it moves through that zone. This will cause the gas, that occurs near the surface, to exit to the atmosphere. More significant displacements of gas will occur with greater quantities of infiltration and/or greater proportions of gas-filled pores so that it is expected that this process is most effective in coarse-grained deposits during spring melt and during the rainy autumn season.

The effects of barometric pumping and gas displacement are not well defined. However, some studies have shown that good simultions of radon concentrations in the tailings and fluxes at the surface can be performed by considering diffusion as the only transport mechanism. Modelling by this approach suggests that slime-enriched tailings would result in lower radon fluxes to the surface than coarse-grained tailings.

FIGURE 2.31: AN EXAMPLE OF THE RELATIONSHIP BETWEEN THE EFFECTIVE POROSITY AND THE EFFECTIVE DEPTH OF TAILINGS THAT INFLUENCES RADON EXHALATION



2.6.3 Revegetation

Establishment of a self-sustaining continuous vegetation cover on uranium tailings is highly desirable since the presence of vegetation eliminates fugitive dust losses, decreases the rate of radionuclide and contaminant leaching and is aesthetically pleasing. Under certain conditions, native species may invade the tailings (Kalin, 1980, 1981). However, in general, establishment of a vegetative cover requires extensive ameliorative measures. Revegetation of pyritic tailings is especially difficult due to low pH and high solubility of toxic elements, such as aluminum. Intensive liming and fertilization are common practices on such tailings and, despite high capital costs, results are generally marginal.

Few revegetation studies on slime-enriched tailings have been conducted to date. However, preliminary work in the Elliot Lake area suggests that the soil environment of slime-enriched tailings is even more limiting to plant growth than that of unsegregated or coarse tailings (Murray, 1971). To date, all attempts to revegetate slimes have proven unsuccessful. Murray (1972) suggests that both physical and chemical factors inhibit the establishment of vegetation. Poor aeration appears to be the major growth limiting factor. The high water retention capacity of slimes results in water tables which are at or near the tailings surface throughout much of the year. Thus, oxygen supply to the plant roots is limited and soil microorganisms which break down organic matter and mediate nutrient cycling are inhibited. As shown in Table 2.17, none of the commonly planted cover species used in tailings revegetation can tolerate prolonged waterlogging. Waterlogging also influences the soil microclimate in that wet soils are colder than well-drained soils. Thus, seed germination and growth are inhibited.

Chemical factors which will affect revegetation of slime-enriched tailings containing pyrite include potentially high acidity, low nutrient content and bioavailability, and mobilization of toxic elements. However, these limitations are encountered in all pyritic tailings. It is interesting to note that Murray (1972) found no significant improvement in plant growth on slimes after liming and fertilization. These results appear to verify the importance of waterlogging as the major growth limiting factor.

While no studies have been conducted on slime-enriched tailings in Saskatchewan, it is likely that the establishment of a vegetative cover would be easier in non-pyritic

TABLE 2.17: TOLERANCE OF FORAGE SPECIES TO FLOODING IN THE SPRING (Murray, 1971)

Crop	No. of Days Flooding Tolerated
Red clover	0-7
Sweetclover	7-14
Alfalfa	7-14
Alsike clover	7-14
Stawberry clover	7-21
Intermediate wheatgrass	21-28
Meadow fescue	21-42
Timothy	21-56
Reed canarygrass	35-56
Slender wheatgrass	35-56
Bromegrass	35-56

*

tailings. However, in northern Saskatchewan, other factors such as surface instability, drought and low porosity might significantly affect growth.

3.0 MANAGEMENT OF SLIME-ENRICHED TAILINGS

3.1 Introduction

The long-term management of tailings requires a degree of confidence regarding their future behaviour. This knowledge of future behaviour under changing environmental conditions permits planning of monitoring or remedial actions, prediction of environmental effects, and provides guidelines with which to judge the acceptability of a wide range of management options. In a general sense, the more rapidly conditions change within a tailings management area, the more difficult it becomes to predict future environmental conditions. As a result, the most attractive types of management options are those which incorporate a high degree of inherent stability into their design. This stability which is, for the purposes of this report, defined in terms of geotechnical, geochemical and environmental parameters, implies that changes will not be excessively rapid and will occur in a well understood manner which do not result in unacceptable environmental consequences.

Although the tailings parameters, which influence the geotechnical, geochemical and biological processes occurring in slime-enriched tailings, are discussed separately in this report, it is important to recognize that these processes are all interrelated. Any change in the physical nature of the tailings related to subsidence or a washout may be expected to have an effect on geochemical processes within the tailings and biological processes within and on the tailings. Similarly, geochemical changes within the tailings, such as pyrite oxidation, may alter geotechnical properties (e.g., porosity related to mineral dissolution) and biological properties (e.g., increased acidity and toxic trace elements concentrations in the plant root zone). Changes in the biological community inhabiting a tailings area may also be expected to affect geotechnical properties (e.g., disease or fire may reduce vegetative cover thus affecting the water balance and this in turn can affect geotechnical properties such as degree of saturation and geochemical properties such as oxygen penetration into the tailings).

The degree of interrelationship of the geotechnical, geochemical and biological properties both among themselves and with the external environment is highly site-specific. It is necessary to understand the range of variation in fundamental properties of slime-enriched tailings in order that their long-term stability may be predicted. For

example, if slimes are held behind a conventional dam structure, the geotechnical, geochemical and biological stability of the tailings management area will all be strongly influenced by the water balance in the tailings which can change seasonally or over a period of many years in response to long-term seasonal climatic change. At another site, where slimes are held under water (e.g., on the bottom of a lake basin), seasonal climatic changes may not affect the water balance, but more long-term changes may influence regional water balance and through it groundwater flow patterns in and around the tailings.

The focus of this section is to provide that description of the key geotechnical, geochemical and biological interrelations which will affect management options in slime-enriched uranium mine tailings under a variety of environmental conditions.

The specific aspects of tailings management considered in this section are:

- o overall mass stability
- o drainage, settlement and site accessibility
- o dusting/water erosion
- o overall water balance/seepage
- o reclamation

3.2 Overall Mass Stability

As noted in Section 2.4, tailings deposited hydraulically at low pulp densities are generally deposited in a relatively loose state. However, it was concluded that slimes are probably less susceptible to liquefaction than coarser tailings. Most historic failures of tailings dams and hydraulic fill dams have occurred in areas subjected to strong seismic activity, e.g. Chile and California. In such areas, special care may be required to ensure that the surrounding dams are seismically stable and/or that long internal beaches cannot liquefy and overtop perimeter dams.

If there is a potential for liquefaction of the tailings which could lead to dam failure or overtopping, measures to compact the tailings would be required. These might include draining of tailings by underdrains or alternative dewatering techniques, preloading, blasting to induce consolidation and/or using vibratory compactors (for further discussion

of each process, see Nelson et al., 1983). The feasibility of any of these would be dependent on the characteristics of the specific tailings slimes. It should be noted that underdrainage does not require access to the surface of the tailings after the completion of tailings deposition, but all the other processes listed above do.

With these latter processes, the tailings are generally in a loose state at the end of deposition and are compacted afterwards. This may pose some hazard in the event of a significant seismic event during deposition. Underdrainage, if it could be successfully applied, would result in a more dense tailings deposit during deposition. Alternative placement methods would include both thickened tailings and sub-aerial tailings deposition but neither of these is applicable if the clay content of the slimes is high; in addition, the verification of the overall seismic stability of either thickened or sub-aerial tailings is no easier than that of ordinary tailings.

In summary therefore, the overall geotechnical stability of tailings slimes deposited hydraulically in a loose state may be adequate in regions of low to negligible seismicity. In areas of moderate to high seismicity, one of several special processes may be required to ensure the adequate overall stability of the tailings; some of these special processes to densify the tailings require access to the surface of the tailings.

3.3 Drainage, Settlement and Site Accessibility

During deposition, many tailings are saturated with the water table close to the ground surface. Under these conditions, it is often impossible to walk on the tailings, let alone gain vehicular access. The position of the water table following the cessation of tailings deposition will be governed by the climate, proportion of surface runoff and external drainage conditions, e.g. permeability and water table in the underlying liner, or bedrock and/or surrounding dams.

Site accessibility can be improved if the water table is lowered to at least 1 to 2 metres below the surface of the tailings. However, it should be recognized that the resulting geochemical reactions in pyritic tailings could be undesirable and access via a tracked vehicle would probably still be required. Lowering of the water table would also produce settlement of the underlying tailings, as would any of the processes considered in the previous section to improve mass stability. In high slimes areas, the resulting settlements could be large and might take several years.

In certain situations an engineered cover is a cost effective method of minimizing erosion, limiting infiltration, reducing radon exhalation rates or reducing oxygen entry into the tailings. Access and consolidation/settlement of the tailings become crucial aspects to consider when this method is employed. Heavy earthmoving equipment can easily become bogged down in soft or loose tailings and the placement of any cover may require the prior regrading of the surface of the tailings. This may be more difficult in slimes than in sand tailings.

The placement of an engineered cover will lead to consolidation/settlement of the underlying tailings. Such settlements will be much greater in areas of slimes, if slime-enhanced tailings are used, than in areas of sandy tailings. The differential settlement of tailings surfaces and its effect on engineered covers was discussed by Nelson et al. (1983). They noted that the amount of differential settlement that can be tolerated will depend to a large extent on the cover system being used. A cover of cohesionless material with a thickness of one metre or more could tolerate settlement on the order of one metre.

On the other hand, in order to decrease the amount of cover material required, some tailings management plans in the USA have proposed to utilize a clay cap, on the order of 0.3 m thick immediately over the tailings, covered by granular, cohesionless material. Nelson et al. (1983) indicated that differential settlement in the amount of 0.3 m in a 3 m length would produce tensile strains on the order of 0.1 percent in the clay liner which could produce cracking. They, therefore, concluded that the maximum settlements that can be tolerated by clay caps would be on the order of 0.1 to 0.2 m, if the radon attenuation characteristics of the clay cap are not to be compromised. Similar reasoning would also apply to limiting infiltration or oxygen entry through engineered covers in Canada.

Nelson et al. (1983) noted that synthetic materials might be able to withstand larger differential settlements than clay, but again emphasize the need to accelerate settlement in advance of construction of any engineered cover in order to minimize post-construction differential settlements.

3.4 Dusting/Water Erosion

Problems of both dusting and/or water erosion are most severe for fine sand and silt particles, i.e. for typical tailings materials (see for example, Walters et al., 1983). In both cases, the most direct form of prevention is generally vegetation or an engineered cover if the tailings are exposed. To carry out such a process could require access to, and drainage of, the tailings after the cessation of deposition, although Chakravatti et al. (1982) attempted to add grass seed at the mill during the construction of Denison Mines' experimental mini-cone of thickened tailings in Elliot Lake.

Another alternative would be to flood the tailings. Although this could be a very good solution in a natural basin, it is generally regarded that long-term dam stability and potential for downstream detriment is not diminished by maintaing a perpetual tailings pond after close-out. Where there are large man-made structures, it is considered preferable to eliminate any such pond at the end of active tailings deposition.

3.5 Overall Water Balance/Seepage

The presence of slime-enhanced tailings will tend to increase the relative proportion of surface runoff and decrease the potential for precipitation infiltration into the tailings. However, the in situ permeability of hydraulically-deposited slimes tailings, with low clay contents, is generally not significantly lower than that of sand tailings, due to the presence of more pervious sand lenses or layers. It should not necessarily be concluded, therefore, that slimes will provide a low permeability layer from which seepage will be minimal.

Uranium tailings slimes with high clay contents, such as those in Saskatchewan, may, however, lead to tailings with permeabilities of 10^{-7} to 10^{-8} cm/sec, from which seepage would be lower than from coarser sand tailings.

From a geochemical perspective, the objective is to minimize water flux through the tailings mass. This will, in general, reduce the flux of dissolved components that exit from the tailings mass either as seepage to the surface or to the groundwater zone. This will be true for constituents for which the concentrations in solution are controlled by equilibrium dissolution of appropriate solid phases. For example, gypsum ($CaSO_4.2H_2O$)

dissolution occurs essentially instantaneously to the solubility limit in the pore water system. Because the concentrations of the components (Ca and SO_4) will remain practically constant, regardless of the magnitude of water flux, any reduction in water flux will reduce the flux of the components leaving the tailings.

In contrast, some solids dissolve under kinetic constraints so that the concentration in solution may vary but the flux into solution remains relatively constant. In this way, the flux of constituents exiting the tailings mass would be practically independent of the water flux as long as the water flow is not zero. Feldspar (e.g. $KAlSi_3O_8$) is an example of such a solid. Feldspar dissolution is surface controlled and is independent of many other variables under ambient conditions (BEAK, 1985a). This behaviour indicates that lowering of water flux through the tailings will reduce the flux of some but not all of the dissolved constituents.

Reduction of water flux can be accomplished by appropriate contouring of the surface and by establishment of a healthy vegetative cover that would aid in evapotranspiration of shallow subsurface water. Development of final surface contours may be problematic with the fine-grained tailings because of slope instability in the undrained material. The establishment of vegetation, as discussed below, could be difficult in the moist tailings or surface cover material.

3.6 Reclamation

3.6.1 Inhibition of Pyrite Oxidation

As noted in Section 2.5.4, the oxidation of pyrite in the tailings greatly increases the potential for water quality degradation. Thus environmental objectives for pyritic tailings must focus on the inhibition of pyrite oxidation.

In general, the rate of pyrite oxidation is relatively low in slime-enriched tailings because of high moisture contents. It is, therfore, advantageous to promote high water contents in the tailings. Because of the high moisture retention capacity of the fine-grained slimes within the tailings, saturation, at or near the surface, may be achieved even if the water table is some distance beneath the surface. For example, some silt materials retain water-saturated pores up to the surface with the water table at a depth

of 3 metres or more. Drying of the near-surface zone is probable, however, during summer months if the tailings remain exposed. It may, therefore, be necessary to provide a form of cover on the tailings to prevent drying and subsequent oxygen penetration. Ideal cover material would consist of non-oxidizing fines (Nicholson et al., 1986) that would generally remain moist and would provide a further barrier to oxygen transport into the underlying tailings.

Maintenance of interstitial water throughout the tailings and placement of a cover over the slime-enriched tailings would minimize concentrations of many constituents of concern in the tailings pore water. These conditions may, however, minimize the geotechnical stability, and reduce the aesthetic qualities, of the tailings area.

High water table conditions in slime-enriched tailings will likely result in poor consolidation and stability. It would seem appropriate, therefore, to choose optimal water table levels so as to maintain both geotechnical stability and chemical stability. The placement of a cover layer, such as depyritized-unsegregated tailings, if not excessively fine-grained, may contribute to consolidation and subsequent stability of the slime-enriched tailings.

The high moisture content and resulting low aeration of the tailings would be generally undesirable for growth of vegetation. The placement of a cover with a lower moisture retention capacity than that of the tailings could present more favourable conditions for growth. Excessive aeration of the surficial cover, however, would result in increased oxidation within the tailings. Development of vegetation requiring minimal aeration of the root system would be ideal under such circumstances.

3.6.2 Revegetation

As previously noted in this chapter, some form of coverage of the tailings is environmentally desirable as a means of reducing gamma radiation, radon gas exhalation and erosion. To date revegetation has been the preferred ultimate cover on uranium tailings because, once established, a self-perpetuating vegetation cover requires little maintenance and is aesthetically pleasing.

Revegetation strategies commonly employed on uranium tailings include direct revegetation on amended tailings, or coverage of the tailings with a suitable growth substrate followed by revegetation. Vegetation types commonly used in reclamation of uranium mine tailings are grass species, legumes and tree seedlings. Under certain conditions indigenous species will also invade tailings areas (Kalin, 1980, 1981).

Revegetation strategies for slime-enriched tailings will be dependent on a number of site-specific condition including:

- o pyrite content of the tailings,
- o drainage conditions and seasonal water balance, and
- o tailings stability.

However, in terms of geotechnical and geochemical considerations, management options devolve into drained versus undrained. Revegetation strategies based on these two options are discussed in the following sections.

Undrained Tailings

Maintenance of high water tables has been shown to be an effective method of inhibiting pyrite oxidation, and thereby minimizing acid generation and dissolution of radionuclides and trace elements. However, revegetation potential under such conditions is poor. Field trails indicate that anaerobic conditions are major limitations to plant growth, even when pH is adjusted and nutrients are provided. The establishment of non-rooted acidophillic aquatic mosses such as Sphagnum spp. may be a viable alternative for direct revegetation of undrained slime-enriched tailings. Alternatives to direct revegetation of tailings include coverage with a suitable substrate material or flooding. As discussed previously, problems associated with engineered covers relate largely to access by equipment and consolidation. However, if the tailings could be capped and covered with soil, a wide range of revegetation options would be available. Coverage by grasses would likely be the most economical and would allow subsequent secondary succession by tree species. Limitations to planting of tree seedlings would relate primarily to the depth of the cover layer in relation to maximum root penetration.

Underwater disposal is another option for tailings management. Major engineering constraints associated with flooding of existing tailings include construction of an impermeable dam and potential for dam failure. Deep lake disposal of tailings (meromictic) would appear to be the most environmentally-sound underwater option. Once tailings had settled, there would be little chance of biological uptake. Creation of a shallow lake or pond is less attractive. Under shallow water conditions tailings would be resuspended by wind and wave action, resulting in high turbidity and pyrite oxidation within the water column. Consequently, acidic conditions could prevail. Under such conditions seepage from the tailings dam could represent a significant source of downstream aquatic contamination. Over many hundreds of years water quality would be expected to improve through dilution by rainfall and surface drainage. The natural processes could be accelerated by adding a flocculent to accelerate settling. Subsequently, the bottom could be sealed with a liner or articial substrate added. However, this process would be expected to be costly.

Drained Tailings

The geotechnical properties of slimes make drainage exceedingly difficult. However, assuming adequate drainage could be achieved, severe constraints to direct revegetation could exist if pyrite was present in the tailings. Pore water with pH values of less than 2 are common in oxidized pyritic tailings. These would result in toxicity to plants due to the presence of high concentrations of soluble forms of trace contaminants such as aluminum. Surface runoff under such conditions is also likely to be more highly contaminated than from sand tailings.

4.0 CONCLUSIONS AND RECOMMENDATIONS

Fine-grained tailings, or slimes, differ from coarse-grained tailings in a number of key geotechnical and geochemical properties. Thus, it can be expected that certain aspects of the short- and long-term management strategies for slime-enriched tailings impoundments will be significantly different than for non-segregated tailings. These will relate largely to considerations regarding overall mass stability, water balance and reclamation alternatives. Although the geotechnical characteristics of Elliot Lake and northern Saskatchewan slimes appear to be generally similar, differences in geochemical properties (i.e., presence of pyrite in Elliot Lake tailings) arising from the different ore types will affect site-specific management strategies. In addition, differences in climatic conditions between the two areas will affect water balances, chemical and radionuclide releases to downstream aquatic systems, the atmosphere and vegetation.

At the present time, there is a lack of quantitative site-specific data for slime tailings. This is especially true for the northern Saskatchewan mining areas. Since it appears that northern Saskatchewan will be the most active uranium development area in Canada in the future, efforts should be made to collect relevant information from existing tailings and management alternatives. Because of the general paucity of data, it is difficult at the present time to assess aspects of slime-enriched tailings management such as relative costs of stabilization and reclamation in comparison to more conventional non-segregated tailings areas, tailings effluent quantity and quality, fugitive dust emissions, and revegetation strategies.

A number of recommendations are made below for specific studies which are considered essential to decision-making regarding the overall feasibility of sand-slime separation as it pertains to the short- and long-term management of slime-enriched tailings:

- One area of concern is the overall mass stability of the tailings. Although slimes appear to be no more, and perhaps even less, susceptible to liquefaction under a seismic event than sand tailings, the determination of when more costly placement methods are necessary in zones of low to moderate seismic activity will be critical.

- Further work on the overall water balance of slime-enriched tailings is required. Specificially, surface runoff, seepage, evapotranspiration and permeability data are required. Such information would have to be collected on a site or climatic region specific basis.

- The oxidation rate of pyrite (and possibly other reduced minerals) appears to be the critical factor in determining the concentrations of many potential contaminants in the slimes tailings pore water. Data for many radionuclides is scarce, however, and it is not clear whether or not the slimes-enriched tailings affects the concentrations of these constituents. Because any effect on the pore water concentration will affect the net flux of a potential contaminant, it is important to known the concentration in the pore water at the less acidic pH values that are expected in the slime tailings. It is, therefore, recommended that more precise data be collected on the concentrations of radionuclides in slime-enriched tailings that exhibit near-neutral pH values. It may also be important to determine the behaviour of such radionuclides when the main sulphate mineral, gypsum, is leached from the slime-enriched tailings.

- The concentrations of some constituents in the tailings pore water are controlled by the equilibrium dissolution of some mineral phases, while concentrations of other constituents result from kinetic controls on dissolution. Knowledge of these processes should be refined so that concentrations, especially for some radionuclides, can be better predicted. It is recommended, therefore, that a review of controlling processes be conducted to determine whether kinetic or equilibrium processes control the concentrations of the radionuclides of concern in the fine-grained fraction of the tailings. The resulting information could then be used to better evaluate the expected fluxes of radionuclides from the tailings.

- Success of revegetation on slime-enriched tailings by current methods has been very limited. The use of non-rooted acidophillic aquatic mosses, such as Sphagnum species, may represent one alternative for revegetation of pyritic waterlogged slimes. Sphagnum toxicity, growth rates and

sensitivity to water table fluctuations on tailings should be examined. In addition, studies on the use of peat moss, sewage sludge and other organic mulches should be conducted on slime-enriched tailings. Preliminary studies on uranium tailings suggest that these materials produce an effective barrier to pyrite oxidation and toxic metals, and provide a source of fertilizer.

- Many (heavily mineralized) areas of Canada have specialized vegetation communities growing on naturally pyrite-rich acidic soils. The particular species/varieties of plants growing in these areas should be investigated as to their potential for colonizing pyrite-rich tailings areas.

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